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WELDBRAZE AIRFRAME COMPONENTS

Northrop Corporation, Aircraft Group
3901 W. Broadway
Hawthorne, California 90250

NOVEMBER 1977

TECHNICAL REPORT AFML-TR-77-171

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G. E. Metzger

G. E. METZGER
Project Monitor

FOR THE COMMANDER:

Nathan G. Tupper

N.G.TUPPER, Chief
Structural Metals Branch
Metals and Ceramics Division
Air Force Materials Laboratory

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The objective of this program was to develop materials and processes necessary to establish weldbrazing as a useful manufacturing technique that satisfies the structural property requirements for advanced aerospace applications.

Several surface preparation methods were evaluated. Spot weld schedules were established for two, three, and four-layer joints; and for three sheet thickness combinations. Methods were developed for determining the proper quantity of filler metal Over

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to be placed at the joint edge prior to brazing and for holding the filler metal in place when weldbrazing in the vertical position.

Lap-joint properties were determined for Ti-6Al-4V with aluminum filler metals 1100, 3003, 4043, 5052, 201, 718, AVCO 48, and Al-32Cu-5Ag. Lap-shear strengths and stress-rupture strengths were obtained at 533K (500F), 617K (650F), and 700K (800F). The elevated temperature lap-shear strength was highest for filler metals 201, 1100, 3003, and 5052. The stress-rupture strength was highest for filler metals 1100 and 201. Filler metals 3003, 1100, 5052, and 4043 had the highest resistance to stress-corrosion and to salt-fog corrosion.

Based on overall properties, filler metals 1100, 4043 and 3003 have the best properties. These alloys provide good lap-shear strength and good corrosion resistance. Filler metal 4043 has the lowest brazing temperature, which is desirable to minimize the formation of the brittle Ti-Al compound.

An evaluation of non-destructive inspection techniques revealed a good correlation between visual inspection ratings for completeness of filler metal flow and approximate percentage of voids at the interface detected by radiography or ultrasonic inspection.

Fatigue behavior and S/N curves were determined for high load transfer and low load transfer weldbrazed joints, using 4043 aluminum filler metal. Fatigue strength of weldbrazed joints and bolted joints is approximately the same for a low-load transfer joint.

A titanium former assembly from the F-5E aft fuselage was weldbrazed using 4043 filler metal. The lap joints present in this assembly included multiple layers with several different sheet thicknesses. Both visual and radiographic inspection indicated that high quality weldbraze joints were obtained. The successful fabrication of this former assembly by using weldbrazing techniques developed during this program has shown the feasibility of using weldbrazing to fabricate airframe components at reduced cost.

PREFACE

This report was prepared by the Northrop Corporation, Aircraft Division, Hawthorne, California, under USAF Contract No. F33615-76-C-5111. The contract work was performed under Project No. 7351, administered under the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Dr. G. E. Metzger was the (AFML/LLS) project engineer.

Northrop Corporation, Aircraft Division, was the contractor, with R. G. Hocker the Program Manager, directing all activities. Other Northrop personnel who made major contributions include:

Joining Technology:	K. C. Wu J. W. Lewis H. R. Miller
Mechanical Tests:	B. J. Mays D. F. Dittmer J. Fitzgerald F. Flower D. Clark
SEM Analysis, Metallography: ...	R. E. Herfert T. Remmel C. Ford J. Schifando D. Anderson
Manufacturing Technology	J. L. Hill P. Adams
Nondestructive Testing:	R. E. Clemens D. L. Kennedy S. Sandor G. Andrews
Structural Analysis:	R. L. LaRose
Cost Estimating:	J. A. Lorenzana
Manager, Materials Research:...	A. H. Freedman
Manager, Metallics Research & Development:	R. R. Wells

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The contractor's report number is NOR-77-115. This final report covers work from 1 May 1976 to 31 August 1977.

SUMMARY

This program was conducted to establish the material and processing parameters necessary for making weldbrazing a useful method for joining titanium aircraft structures. Cleaning methods, spot welding parameters and brazing procedures were evaluated to establish a weldbraze process which could easily be adapted to a manufacturing environment. Weldbraze properties were determined for Ti-6Al-4V joints using several aluminum-base filler metals. Elevated temperature properties and fatigue behavior of weldbrazed joints were determined in order to provide baseline data for weldbraze joint designs. Finally a section of a typical aircraft structure was fabricated using the weldbraze techniques that were established for the program.

Several cleaning methods were evaluated and it was shown that standard cleaning procedures were suitable for titanium weldbraze joint preparation. In general, any procedure which utilized a detergent or alkaline cleaner to remove oil films, followed by a nitric-hydrofluoric acid etch (30% to 40% HNO_3 + 3% HF) with a tapwater and deionized water rinse, was satisfactory for cleaning titanium prior to weldbrazing.

It was demonstrated that high quality spot welds are easily obtained for titanium lap joints. Spot weld schedules were established for multilayer welds for three different sheet thicknesses. The wide permissable range of spot weld schedule parameters permitted high quality spot welds to be made with ease. Radiographic inspection, lap-shear tests, and metallographic examination showed that Class A welds in accordance with MIL-W-6858C are obtained when spot welds are made with the recommended welding schedules. The joint gaps produced by the spot welds are satisfactory for the capillary-flow weldbraze process used in this program.

Methods were developed for determining the amount of filler metal to be placed at the joint edge prior to brazing and for holding the filler metal in place for vertical and inverted joints. Brazing procedures and a brazing environment were selected which resulted in successful filler metal flow into lap joints having gaps ranging from 0.03 mm (0.001 inch) to 0.15 mm (0.006 inch). An evaluation was made for two low melting filler metals to determine if the formation of the brittle Ti-Al intermetallic layer could be avoided.

Weldbraze lap-joint properties were determined for Ti-6Al-4V with aluminum base filler metals: 1100, 3003, 4043, 5052, 201, 718, AVCO 48 and No. 7 alloy (Al-32Cu-5Ag). Lap-shear strength and stress-rupture properties were determined at temperatures up to 700K (800F). The elevated temperature lap-shear strength was highest for filler metals 201, 1100, 3003, and 5052. The stress-rupture strength was highest for filler metals 1100 and 201. Corrosion resistance for weldbraze joints was determined by stress-corrosion tests and by lap-shear strength measurements after 30-day and 60-day salt fog exposure. Weldbrazed joints made with filler metals 4043, 3003, 1100, and 5052 showed good corrosion resistance.

Based on overall properties, filler metals 1100, 4043 and 3003 have the best properties. These alloys provide good lap-shear strength and good corrosion resistance. Filler metal 4043 has the lowest brazing temperature, which is desirable to minimize the formation of the brittle Ti-Al compound.

In order to provide baseline weldbraze data for the designer, fatigue behavior was determined for high load transfer and low load transfer weldbrazed joints fabricated with 4043 filler metal, and compared with mechanical fasteners. For the low-load transfer joint design, the fatigue life of the weldbrazed joint was approximately equal to that of the bolted joint, the spot welded joint and the brazed joint. The comparison of fatigue life between the weldbrazed joint and the bolted joint for the high-load transfer joint was inconclusive due to different overlap dimensions.

The bolted joint has a larger overlap which increased the rigidity of the specimen. Typical aircraft component joints such as the former assembly weldbrazed for this program are generally stiffened by formers, stringers, or ribs which allow minimal bending at the overlap edge. The weldbrazed fatigue specimens had no additional stiffening and therefore the flexing or bending during testing caused higher stresses to occur at the overlap edge than occurred for the stiffer bolted fatigue specimens.

An evaluation of non-destrictive inspection techniques revealed a good correlation between visual inspection ratings for completeness of filler metal flow and approximate percentage of voids at the interface detected by radiography or ultrasonic inspection. Radiography and ultrasonic C-scan inspections provide excellent definition of the size and shape of voids at the faying surfaces. Portable eddy current inspection methods might be developed so that rapid inspection of critical two-layer joints could be performed on the production line as a supplement to visual inspection.

In order to demonstrate the applicability of the weldbraze parameters developed for this program, a former assembly, from the aft fuselage section of an F-5E, was weldbrazed using 4043 filler metal. Spotweld parameters and braze procedures determined during Phase I were used to weldbraze the former assembly. The lap joints present in this assembly included multiple layers with several different sheet thicknesses. Visual inspection and radiographic inspection revealed that high quality weldbraze joints were obtained. Vertical lap joints and inverted horizontal lap joints on the bottom side of the former demonstrated the effectiveness of the capillary flow weldbraze process for complex airframe components. The use of weldbrazing replaced 274 rivets in this assembly resulting in a projected 30% cost savings as determined in a detailed cost study. The successful fabrication of this former assembly by weldbrazing techniques has shown the feasibility of using this process for the fabrication of airframe components at reduced cost.

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SECTION 1

INTRODUCTION

Weldbrazing is a joining process which combines the economy of spot welding with the stress distribution ability of a filler metal to develop a lap joint with attractive static and fatigue strength. Significant cost and some weight reductions can be realized by this joining technique.

The "capillary-flow" weldbrazing method was selected for this program since prior work has shown that it is impractical to use the "weld-through-foil" method. Four basic steps are used to produce capillary-flow weldbrazed lap joints. These steps shown in Figure 1 include:

1. Cleaning the surface of the titanium joint.
2. Resistance spot welding of the joint.
3. Placing aluminum filler metal at the edge of the joint.
4. Heating in a furnace to melt and flow the filler metal.

Examples of weldbrazed lap-joints for two different sheet thicknesses are also shown in Figure 1.

The objective of this program was to develop materials and processes necessary to establish weldbrazing of titanium structures as a useful jointing technique that satisfies the structural property requirements for advanced aerospace applications.

In order to accomplish this objective the following program plan was adopted:

Phase I - Fundamental Studies

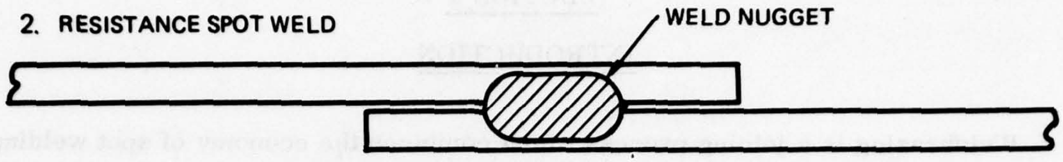
- Task 1 - Cleaning Method Evaluation
- Task 2 - Optimize Spot Welding Parameters
- Task 3 - Optimize Brazing Procedures
- Task 4 - Evaluate Nondestructive Inspection Techniques
- Task 5 - Determine Weldbraze Properties

Phase II - Fabricate an Aircraft Structure

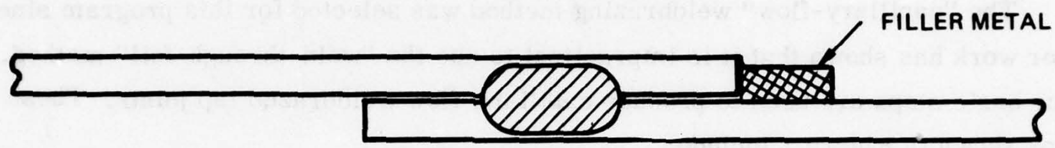
- Task 1 - Select and Weldbraze a Demonstration Aircraft Structure
- Task 2 - Inspect and Evaluate the Weldbrazed Structure

1. CLEAN SURFACE OF THE TITANIUM JOINT

2. RESISTANCE SPOT WELD

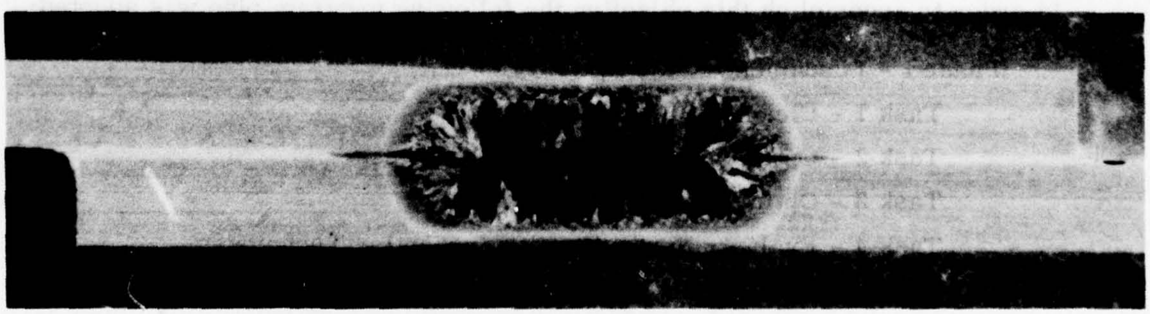


3. PLACE ALUMINUM FILLER METAL AT EDGE OF THE JOINT



4. BRAZE IN FURNACE TO FLOW FILLER METAL

SHEET THICKNESS: 0.5 mm (0.020-inch)



SHEET THICKNESS: 1.6 mm (0.063-inch)

FIGURE 1. CAPILLARY FLOW WELDBRAZE PROCESS

Phase I of this program consisted of fundamental investigations of the basic parameters which control the quality and properties of weldbrazed Ti-6Al-4V structures. For Task 1, several cleaning methods were evaluated to determine which ones are most suitable for preparing titanium joints for spot welding and brazing.

For Task 2, spot welding parameters were optimized for various sheet thicknesses. The effects of welding current, electrode force, and weld time on lap-shear strength, sheet separation, electrode indentation, and nugget diameter were determined. The effects of spot spacing and overlap distance were also determined. The spot welding parameters required to produce Class A welds as defined by MIL-W-6858C were established in terms of lap-shear strength, sheet separation, electrode indentation, and nugget diameter for two-layer, three-layer, and four-layer welds. Percent nugget penetration, porosity, and other internal defects were determined by metallographic examination for spot welds made with the lower and upper welding currents established for the various sheet thickness combinations.

Brazing procedures were optimized in Task 3. Several aluminum alloy filler metals were evaluated. Brazing environments and gravity effects on filler-metal flow for varying joint separations were investigated and filler metal placement methods were developed.

For Task 4 several non-destructive inspection techniques for detecting voids in the weldbraze joint were evaluated. These methods included radiography, ultrasonic C-scan, and eddy current.

Weldbraze properties for 1.6-mm (0.063-inch) Ti-6Al-4V, annealed, were determined in Task 5. Lap-shear strength, stress-rupture properties, cross-tension properties, and corrosion resistance (durability) of weldbraze joints were determined for eight aluminum filler metals: 3003, 718, 4043, 201, No. 7(Al-32Cu-5Ag), 1100, 5052, and AVCO 48. Based on the results of these tests, 4043 was selected as the filler metal to be used to determine the weldbraze joint fatigue behavior. Fatigue tests were conducted for low load transfer and high load transfer joints and the results were compared to similar data for mechanically fastened joints, resistance spot welded joints and brazed joints.

For Phase II of this program, a half section of a titanium former assembly, from the aft fuselage section of an F-5E, was selected to be the weldbraze demonstration sample. The joints in this former assembly contain several different sheet thickness and multiple layer combinations. Vertical lap joints and inverted horizontal lap

joints on the bottom side of the former demonstrated the effectiveness of the capillary flow weldbraze process for complex airframe components. Spotweld parameters and braze procedures determined during Phase I were used to weldbraze the former assembly. Visual inspection and radiography was used to inspect the joints. A cost analysis was made for the riveted and the weldbrazed former assembly.

SECTION 2

TECHNICAL DISCUSSION

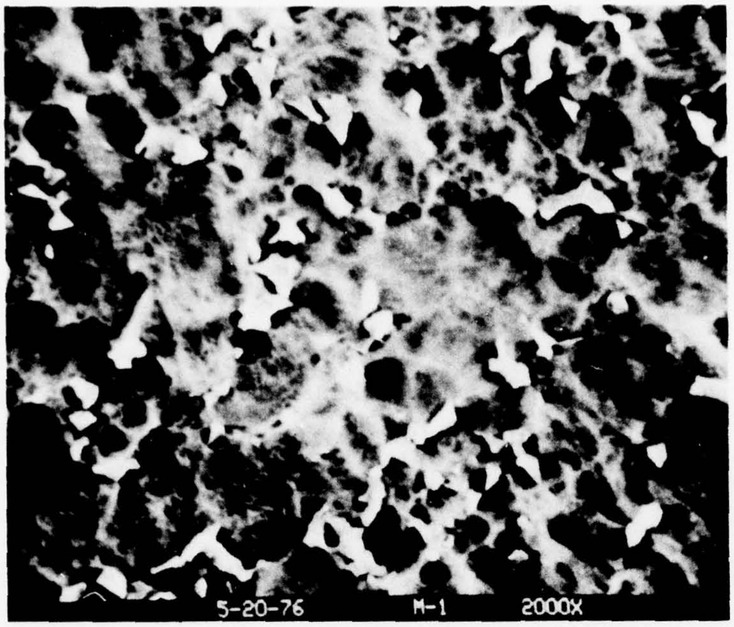
CLEANING METHODS

Several cleaning methods were evaluated in order to determine which ones are the most suitable for preparing the surface of titanium for spot welding and brazing. The eight cleaning methods listed in Table 1 were evaluated using scanning electron microscopy (SEM) and Auger electron spectographic techniques to determine the extent of residual surface contamination. Auger spectographic techniques were also used to determine the oxide layer thickness remaining on the titanium which had been cleaned by methods CM-4 and CM-5. Filler-metal (alloy 4043) flow tests were conducted both in an argon environment and in a vacuum to determine the influence of cleaning methods CM-1 through CM-6 on filler-metal flow in the two brazing environments.

TABLE 1. CLEANING METHODS FOR Ti-6A1-4V WELDBRAZING

CODE	*CLEANING METHOD (1)*	TIME	TEMP.
CM-1	Alconox (Approx. 1 cup Alconox per gallon of water)	10 Min.	Room Temp.
CM-2	CM-1 plus Turco No. 5578	5 Min.	355K to 367K (180F to 200F)
	Desmut with 10% HNO_3, 90% H_2O	1 Min	Room Temp.
CM-3	CM-1 plus Turco No. 5578	5 Min.	355K to 367K (180F to 200F)
	Rinse with Tap Water	5 Min.	Room Temp.
	Desmut with 37% HNO_3, 3% HF, 60% H_2O	3 Min.	Room Temp.
CM-4	CM-1 plus 37% HNO_3, 3% HF, 60% H_2O	3 Min.	Room Temp.
CM-5	Scrub with cleanser (Ajax) and Scotch-brite Pad		
CM-6	CM-1 plus Turco No. 5578	5 Min.	355K to 367K (180F to 200F)
CM-7	CM-1 plus 37% HNO_3, 5% HF, 58% H_2O	3 Min.	Room Temp.
CM-8	CM-1 plus 37% HNO_3, 7% HF, 56% H_2O	3 Min.	Room Temp.

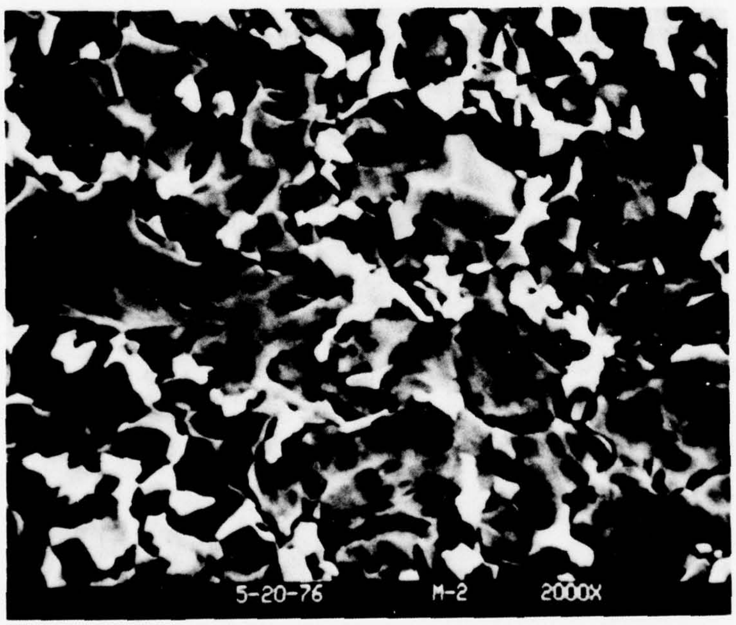
(1) A final 5-minute tap water rinse followed by a 5-minute deionized water rinse at room temperature was part of each cleaning method. Immersion was used in all cases except for scrubbing in CM-5.



370

CM-1

ALCONOX – 10 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.



371

CM-2

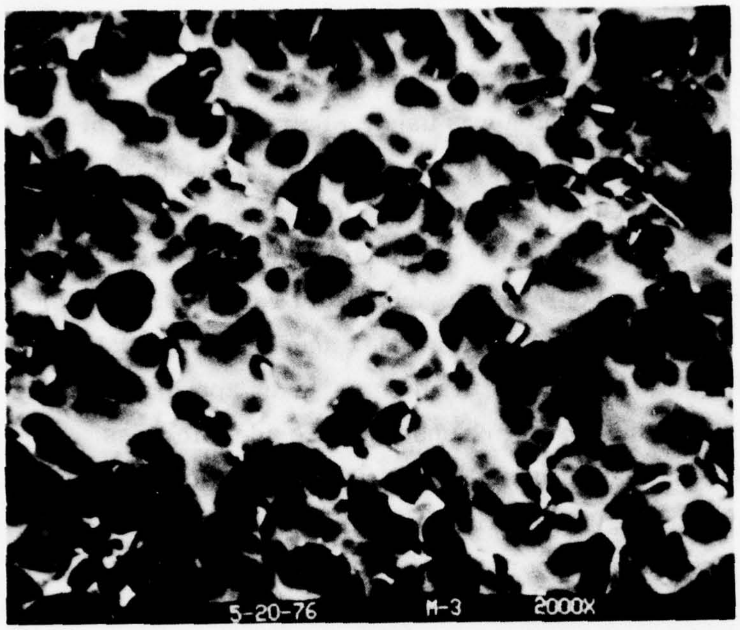
ALCONOX – 10 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.
PLUS
TURCO NO. 5578 - 5 MIN., 355K TO 367K (180F–200F)
10% HNO_3, 90% H_2O – 1 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.

FIGURE 2. SURFACES OF Ti-6Al-4V RESULTING FROM CLEANING METHODS CM-1 AND CM-2

Scanning Electron Microscopy

The results of the SEM analyses showed that the surface appearance was similar for all cleaning methods in which a chemical etch was used, Figures 2 through 5. The beta phase was etched in relief to the alpha phase. The surface appearance relating to cleaning method CM-5, Figure 4, reveals a smeared titanium surface that resulted from scrubbing the surface with a Scotchbrite pad. Cleaning method CM-4 was modified to determine if increased amounts of hydrofluoric acid would result in a cleaner surface; i.e., 3% HF for CM-4 compared to 5% HF for CM-7 and 7% HF for CM-8. The SEM analysis showed that the CM-7 and CM-8 titanium surfaces appeared slightly cleaner, Figure 5 compared to Figure 3. However, subsequent oxide thickness measurements and filler flow characteristics revealed that CM-4 was a completely satisfactory cleaning method for obtaining high quality spot welds and high quality braze joints. The use of hydrofluoric acid in percentages greater than 3% may increase the risk of hydrogen contamination. Therefore, cleaning methods CM-7 and CM-8 are not recommended for cleaning the surface of Ti-6Al-4V.

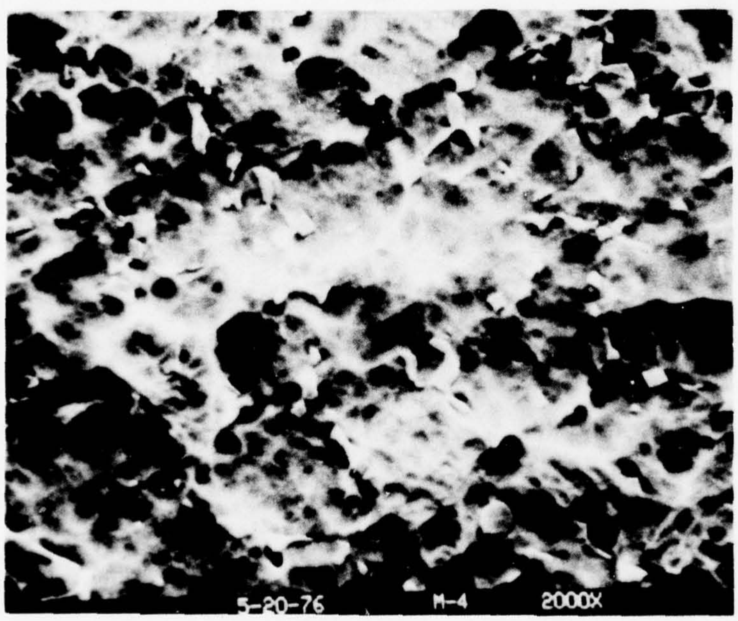
Additional SEM analyses were conducted for Ti-6Al-4V which had been cleaned by methods CM-1 through CM-6 and then exposed to an argon environment at 920K (1200F) at 40 kPa (300 torr) pressure, and to a vacuum environment at 945K (1240F) to determine if the brazing environment would change the surface appearance resulting from each cleaning method. The results of these SEM analyses revealed that the brazing environment did not change the visual appearance of the titanium surfaces produced by the six cleaning methods.



372

CM-3

ALCONOX – 10 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.
PLUS
TURCO NO. 5578 - 5 MIN., 355K TO 367K (180F–200F)
TAPWATER RINSE – 5 MIN., R.T.
37% HNO_3, 3% HF, 60% H_2O – 3 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.

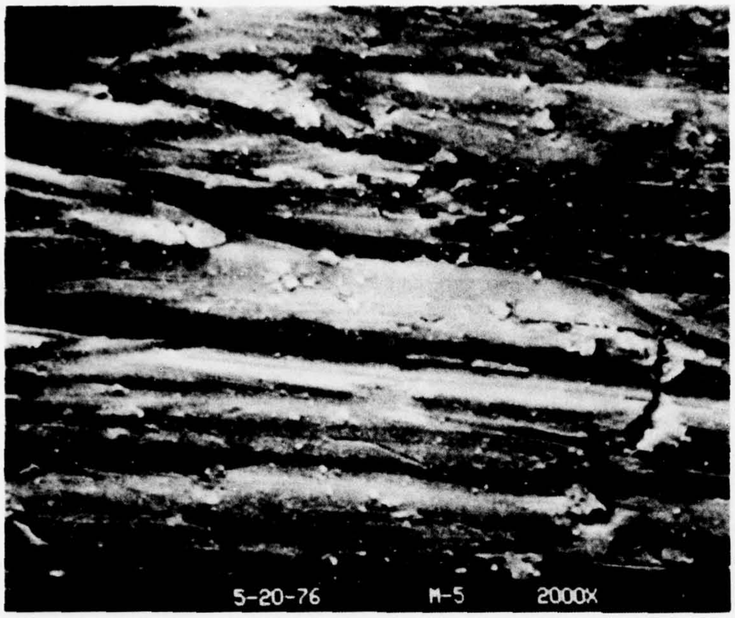


373

CM-4

ALCONOX – 10 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.
PLUS
37% HNO_3, 3% HF, 60% H_2O – 3 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.

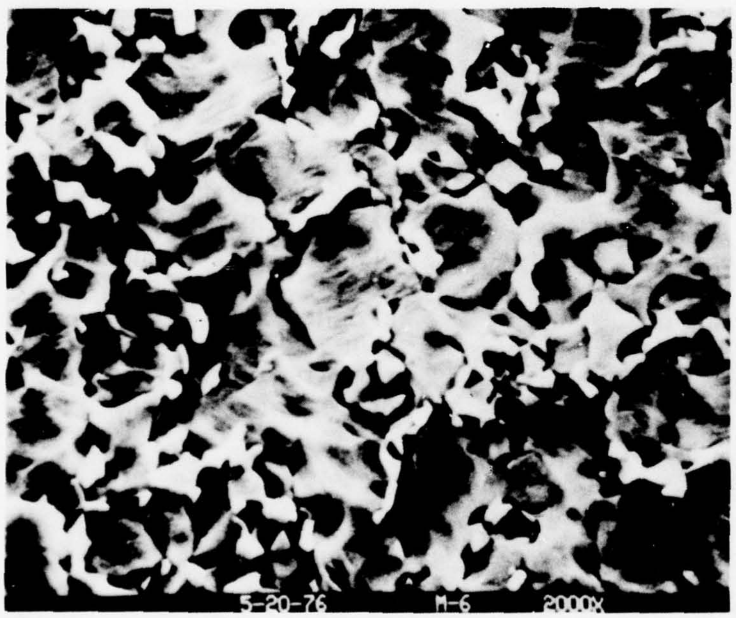
FIGURE 3. SURFACES OF Ti-6Al-4V RESULTING FROM CLEANING METHODS CM-3 AND CM-4



374

CM-5

SCRUBBED WITH CLEANSER (AJAX) AND SCOTCHBRITE PAD AT R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.

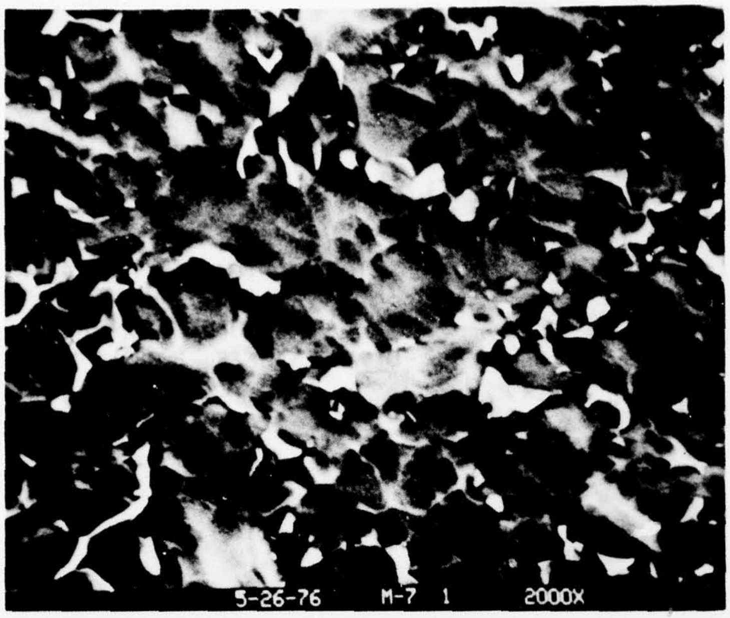


375

CM-6

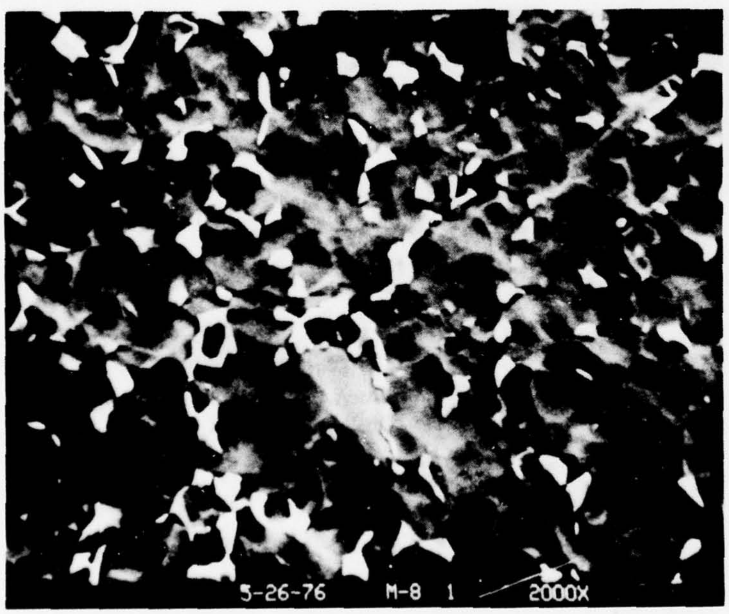
ALCONOX – 10 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.
PLUS
TURCO NO. 5578 - 5 MIN., 355K TO 367K (180F–200F)
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.

FIGURE 4. SURFACES OF Ti-6Al-4V RESULTING FROM CLEANING METHODS CM-5 AND CM-6



CM-7

ALCONOX – 10 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.
PLUS
37% HNO_3, 5% HF, 58% H_2O – 3 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.



CM-8

ALCONOX – 10 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN., R.T.
PLUS
37% HNO_3, 7% HF, 56% H_2O – 3 MIN., R.T.
TAPWATER RINSE – 5 MIN., R.T.
DI WATER RINSE – 5 MIN. R.T.

FIGURE 5. SURFACES OF Ti-6Al-4V RESULTING FROM CLEANING METHODS CM-7 AND CM-8

Auger Spectrographic Analysis

Auger analysis was used to determine whether any residual surface contamination remained after the cleaning method. The results are shown in Table 2. The trace of phosphorous (P) remaining on surfaces cleaned by CM-1 and CM-5 can be attributed to the phosphorous contained in the Alconox and Ajax cleaning compounds. The iron (Fe) remaining from CM-1, CM-2, CM-5, and CM-6 may have been imbedded on the surface of the titanium sheet during the rolling operation, and then etched away by the 37% HNO_3 - 3% HF solution used for CM-3 and CM-4. The sodium (Na) remaining for CM-2 and CM-6 is probably found in Turco 5578 and was etched off the surface for CM-3 by the 37% HNO_3 - 3% HF solution. The trace of fluorine (F) remaining on the CM-3 and CM-4 surfaces corresponds to the 3% HF used for these cleaning methods. The copper (Cu), zinc (Zn), and silicon (Si) found on the CM-5 surfaces was probably caused by contamination picked up from the Scotchbrite pad or from trace elements in the Ajax cleanser.

TABLE 2. RESIDUAL SURFACE TRACE ELEMENTS

CLEANING METHOD (DETAILS IN TABLE 1)	TRACE ELEMENTS ON SURFACE						
	P	Fe	Na	F	Cu	Zn	Si
CM-1 (Alconox)	X	X					
CM-2 (Turco 5578 - 10% HNO_3)		X	X				
CM-3 (Turco 5578 - 37% HNO_3 - 3% HF)				X			
CM-4 (37% HNO_3 - 3% HF)				X			
CM-5 (Scrubbed - Ajax, Scotchbrite Pad)	X	X			X	X	X
CM-6 (Turco 5578)		X	X				

Auger spectographic analysis was also used to determine the thickness of the residual oxide layer for cleaning methods CM-4 and CM-5. Method CM-4 was selected for this evaluation because it is the common cleaning method used for cleaning Ti-6Al-4V prior to spot welding and brazing. Method CM-5 was selected because this cleaning method is believed to retain a maximum oxide layer thickness after cleaning compared to the other cleaning methods. The results of these analyses showed that the residual oxide layer thickness was approximately 250Å for cleaning method CM-4 and approximately 350A for cleaning method CM-5. Subsequent evaluation has shown that oxide layers of this small magnitude do not inhibit the successful formation of spot welds or brazements.

Filler-Metal Flow Tests

Flow tests were conducted to evaluate the influence of cleaning methods CM-1 through CM-6 on filler-metal flow in two brazing environments, argon and vacuum. Braze flow specimens consisted of a 25 mm (1 inch) square panel spot welded to a 38 mm (1.5-inch) square panel of 1.6 mm (0.063-inch) thick Ti-6Al-4V. A titanium foil cover was made to surround each flow specimen for each run to prevent possible furnace contamination of the specimens. An equal quantity of 4043 filler metal was placed at one edge of each small panel for all flow tests. All specimens were brazed in a cold-wall vacuum furnace.

For the vacuum brazing environment, a vacuum of 1.33mPa (10^{-5} torr) was obtained. The flow specimen was heated to 945K (1240F) maximum. For the argon brazing environment, the furnace was heated to 590K (600F) in a vacuum, backfilled with argon to a partial pressure of 40 kPa (300 torr), and then heated to 922K (1200F) maximum. The specimens were heated to the maximum temperature in approximately 50 minutes, held at that temperature for five minutes, and furnace-cooled to room temperature in one-half to one and one-half hours, depending on the size of the furnace load.

These procedures were used throughout the program for the two brazing environments used in the cold-wall vacuum furnace. Prior braze investigations which used 4043 filler metal revealed that the higher braze temperature is required for the vacuum environment in order to obtain good filler-metal flow.

A separate flow test was made for each cleaning method so that the flow temperature could be observed and so that possible surface contamination from one cleaning method would not contaminate the other samples. A rating for each cleaning

method as related to each brazing environment was noted. These ratings are based on observed filler-metal flow temperature, completeness of filler-metal flow around the edge of the smaller titanium square, and degree of filleting. A higher rating was given to the cleaning method which resulted in a lower observed filler-metal flow temperature, since this condition indicates that the surface has better wetting and flow characteristics than a surface for which a high flow temperature was observed. The results of these evaluations are shown in Table 3. In addition to visual analyses of the filler-metal flow specimens, all samples were inspected by ultrasonic "C" scan techniques. All twelve flow samples exhibited complete filler-metal flow to the spot weld nugget.

TABLE 3. EFFECT OF CLEANING METHOD AND BRAZING ENVIRONMENT ON 4043 FILLER-METAL FLOW CHARACTERISTICS

CLEANING METHOD (DETAILS IN TABLE 1)	BRAZE ENVIRONMENT	OBSERVED FILLER-METAL FLOW TEMPERATURE	FILLER-METAL FLOW*	DEGREE OF FILLETING
CM-1 (Alconox)	Vacuum	922K (1200F)	Excellent	Partial
	Argon	922K (1200F)	Excellent	Full
CM-2 (Turco 5578 - 10% HNO_3)	Vacuum	902K (1165F)	Incomplete	Negligible
	Argon	922K (1200F)	Excellent	Full
CM-3 (Turco 5578 - 37% HNO_3 - 3% HF)	Vacuum	944K (1240F)	Excellent	Negligible
	Argon	916K (1190F)	Excellent	Full
CM-4 (37% HNO_3 - 3% HF)	Vacuum	944K (1240F)	Excellent	Partial
	Argon	905K (1170F)	Excellent	Full
CM-5 (Scrubbed - Ajax Scotchbrite Pad)	Vacuum	922K (1200F)	Excellent	Negligible
	Argon	916K (1190F)	Excellent	Full
CM-6 (Turco 5578)	Vacuum	922K (1200F)	Incomplete	Negligible
	Argon	928K (1210F)	Excellent	Full

* **Braze Flow: Excellent - 100 percent flow along four edges of small panel**

Argon Brazing Environment: Excellent filler-metal flow and full fillets were formed in the argon brazing atmosphere for flow specimens representing all six cleaning methods, as shown in Table 3. However, the observed filler-metal flow temperature did vary slightly. The lowest flow temperature of 905K (1170F) occurred for the CM-4 surface, which indicates that this surface may have slightly improved wetting and flow characteristics as compared to the surfaces representing the other cleaning methods for which the flow temperatures exceeded 916K (1190F).

Vacuum Brazing Environment: Only negligible or partial filleting occurred in the vacuum brazing environment for flow specimens representing the six cleaning methods, CM-1 through CM-6. Cleaning methods CM-1 and CM-4 produced partial fillets compared to negligible fillets for the other cleaning methods.

Surface Contact Resistance

A surface contact resistance range of 100 to 300 micro-ohms was measured for Ti-6A1-4V cleaned by the above cleaning methods. The surface resistance for Ti-6A1-4V which has been cleaned by method CM-4 is 150 to 250 micro-ohms. High quality welds have been consistently obtained using this cleaning method, and since the surface resistance obtained for this method is in the same range as that obtained for all the cleaning methods; these cleaning methods will produce class A welds when proper spot welding parameters are utilized.

Manufacturing Cleaning Method

In addition to evaluating cleaning methods developed in the laboratory a standard manufacturing cleaning method, CM-9, was evaluated with the SEM and a filler-metal flow test. This cleaning method includes chemical cleaning both prior to and after the hot forming of titanium at 1005K (1350F). The following procedures were used both in the manufacturing area to clean the T1-6Al-4V samples and in the laboratory to simulate the hot forming cycle:

1. Cleaning Prior to the Hot Forming Cycle:

Delchem 2368A, 60 gm/liter (8 oz/gal)	355K (180F)	15 minutes
Tap Water Rinse	R.T.	5 minutes

2. Hot Forming Cycle:

Apply Graphite Lubricant, less than 0.03 mm (0.001-inch) thick		
Heat Samples in Air	1005K (1350F)	30 minutes

3. Cleaning After the Hot Forming Cycle:

Delchem 2368A, 60 gm/liter (8 oz/gal)	355K (180F)	15 minutes
Tap Water Rinse	R.T.	5 minutes
Turco 4316, 770 gm/liter (6.4 lb/gal)	411K (280F)	15 minutes
Tap Water Rinse	R.T.	5 minutes
Nitric-Hydrofluoric Acid ($37\%\ HNO_3 - 2\%\ HF - 61\%\ H_2O$)	R.T.	3 minutes
Tap Water Rinse	R.T.	5 minutes
Hot Rinse With Deionized Water		3 minutes

The surface appearance, as shown by the SEM, for the Ti-6Al-4V cleaned by CM-9 is similar to that obtained for all prior cleaning methods in which a chemical etchant was used. Excellent filler-metal flow occurred on the Ti-6Al-4V which was cleaned by CM-9 and then brazed with 4043 filler metal at 920K (1200F) in a 40 kPa (300 torr) argon environment.

Shelf-Life And Contamination Evaluation

An evaluation was conducted to determine the shelf life of cleaned titanium surfaces and the effect of fingerprint contamination on weldbraze joints. Specimen blanks for filler-metal flow evaluation and lap-shear tests were sheared from Ti-6Al-4V, 1.6 mm (0.063-inch) and then cleaned by method CM-4. Two sets of flow specimens and six sets of lap-shear specimens were subjected to each of three conditions: fingerprints, cotton gloves, and plastic gloves. One-half of the specimens for each condition were exposed to the open laboratory air for one month. The remaining specimens for each condition were wrapped in Kraft paper for one month. After one month of exposure, the surface resistance was found to be 700 to 1500 micro-ohms for the fingerprinted specimens exposed to air and 150 to 250 micro-ohms for specimens handled by cotton gloves and plastic gloves. Even though the surface resistance was much higher for the fingerprinted specimens, all samples exhibited the same current flow of 10,000 amperes when spot welded using the same spot weld parameters. This would indicate that surface resistance of up to 1500 micro-ohms will not degrade the quality of the spot weld. The high electrical resistance of the titanium base metal apparently nullifies the effect of the higher surface resistance noted above.

Filler-metal flow tests were conducted in an argon environment. Excellent filler-metal flow and filleting occurred for all samples, including the fingerprint samples. For the weldbrazed lap-shear tests, all failures occurred in the base metal, indicating high quality weldbraze joints. A 19 mm (0.75-inch) overlap was used for these tests.

Cleaning Method Summary

Based on the SEM analyses, Auger analyses, and filler-metal flow test results, it is recommended that cleaning methods CM-1, CM-3, CM-4, or CM-5 (or equivalent methods) be used to prepare mill-descaled Ti-6Al-4V surfaces for spot welding and brazing. Methods "equivalent" to CM-3 and CM-4 can be defined as ones which utilize a detergent or alkaline cleaner to remove oil films, followed by a nitric-hydrofluoric acid etch (30% to 40% HNO_3 + 3% HF), with a tapwater and deionized water rinse. The standard manufacturing cleaning method, CM-9, used prior to and after the hot forming of titanium is also satisfactory for preparing titanium for weldbrazing.

In general, any procedure which utilizes a detergent or alkaline cleaner to remove oil films, followed by a nitric-hydrofluoric acid etch (30% to 40% HNO_3 + 3% HF) with a tapwater and deionized water rinse, is satisfactory for cleaning Ti-6Al-4V prior to weldbrazing.

The results of the contamination evaluation indicate that the handling of titanium by fingers, cotton gloves, and plastic gloves with one month exposure in air or in Kraft paper will not degrade either the spot welds or brazing filler-metal flow. Fingerprint contamination of titanium surfaces which are to be weldbrazed is not recommended. However, the results of this contamination evaluation show that the weldbraze joining technique is reasonably tolerant of possible surface contamination that might occur during production fabrication.

RESISTANCE SPOT WELDING PARAMETERS

Resistance spot welding parameters were determined for mill annealed Ti-6Al-4V using a single phase resistance spot welding machine. The effect of the spot weld spacing and spot weld to edge distance (overlap) on lap-shear strength was determined for 1.6 mm (0.063-inch) Ti-6Al-4V. The effect on weld current, electrode force, and weld time on lap-shear strength, sheet separation, electrode indentation, and nugget diameter was determined. Based on this information, weld schedules were established which produce Class A welds in accordance with MIL-W-6858C. Metallographic examination was used to measure nugget penetration, nugget diameter, sheet separation, surface indentation, and weld porosity for the low and high welding currents established as the optimum weld current range.

Spot Weld Spacing And Overlap Distance

In the fabrication of lap joints by resistance spot welding a question often arises as to the effect of minimum spot spacing (shunting of the welding current) on the formation of Class A welds. Another variable to be considered is the overlap distance which controls the distance between the spot and the sheet edge.

In order to determine the effect of spot weld spacing and overlap distance on lap shear strength, the following test program was conducted. Individual test panels were spot welded with spot spacing dimensions of 13 mm (0.5 inch), 19 mm (0.75 inch), 25 mm (1.0 inch), 38 mm (1.5 inch), and 50 mm (2.0 inch) using an overlap distance of 19 mm (0.75 inch). Three lap-shear specimens were saw cut from each panel, providing three test specimens for each spot spacing dimension.

Lap-shear specimens were also spot welded using 25 mm (1.0-inch) wide by 100 mm (4.0-inch) long blanks so that three specimens could be tested for each of three overlap distances, 13 mm (0.5 inch), 19 mm (0.75 inch), and 25 mm (1.0 inch).

A predetermined weld schedule was used which consistently provided Class A welds in the 1.6 mm (0.063-inch) Ti-6Al-4V sheet with lap shear strengths of 17800 to 18700 N (4000 to 4200 lb.).

The results of these spot spacing and overlap tests, presented in Table 4, show no significant change in lap-shear strength for a change either in spot spacing or overlap distance. The slightly lower strength (7%) indicated for the 13 mm (0.5-inch) and 19 mm (0.75-inch) spot spacing represents base metal strength, not the strength of the spot weld. Since failure occurred in the base metal, the strength of the nugget is higher than shown in Table 4. It is believed that, since the nugget diameter 7.1mm (0.28 inch) was equal for all specimens, their lap-shear strengths would be equal. Therefore, any current shunting effect that may have occurred at close spacing is considered to be negligible.

Based on these results all lap-shear specimens used throughout the program for the weldbraze property tests were spot welded using the same weld schedule. All specimens had an overlap distance of 19mm (0.75) which is typically used for this material thickness of 1.6 mm (0.063 inch).

TABLE 4. EFFECT OF SPOT WELD SPACING AND OVERLAP DISTANCE ON LAP-SHEAR STRENGTH

<table>
<tr><th rowspan="2">SPECIMEN</th><th colspan="2">SPOT SPACING</th><th colspan="2">OVERLAP DISTANCE</th><th colspan="2">LAP-SHEAR STRENGTH</th></tr>
<tr><th>mm</th><th>(inch)</th><th>mm</th><th>(inch)</th><th>N</th><th>(lb)</th></tr>
<tr><td>7-6
7-8
7-10</td><td>13
13
13</td><td>(0.5)
(0.5)
(0.5)</td><td>(2)</td><td>(2)</td><td>16000
16900
16450</td><td>(3600)(1)
(3800)(1)
(3700)(1)</td></tr>
<tr><td>10-1
10-3
10-6</td><td>19
19
19</td><td>(0.75)
(0.75)
(0.75)</td><td>(2)</td><td>(2)</td><td>16250
16000
17800</td><td>(3650)(1)
(3600)(1)
(4000)</td></tr>
<tr><td>5-2
5-3
5-6</td><td>25
25
25</td><td>(1.0)
(1.0)
(1.0)</td><td>(2)</td><td>(2)</td><td>17800
18000
17800</td><td>(4000)
(4050)
(4000)</td></tr>
<tr><td>8-1
8-2
8-4</td><td>38
38
38</td><td>(1.5)
(1.5)
(1.5)</td><td>(2)</td><td>(2)</td><td>18000
18000
17900</td><td>(4050)
(4050)
(4025)</td></tr>
<tr><td>9-1
9-2
9-3</td><td>51
51
51</td><td>(2.0)
(2.0)
(2.0)</td><td>(2)</td><td>(2)</td><td>17350
18450
18000</td><td>(3900)
(4150)
(4050)</td></tr>
<tr><td>76-A-30
76-A-31
76-A-32</td><td>(3)</td><td>(3)</td><td>13
13
13</td><td>(0.5)
(0.5)
(0.5)</td><td>18250
18700
18250</td><td>(4100)
(4200)
(4100)</td></tr>
<tr><td>76-A-33
76-A-34
76-A-35</td><td>(3)</td><td>(3)</td><td>19
19
19</td><td>(0.75)
(0.75)
(0.75)</td><td>18700
18250
18450</td><td>(4200)
(4100)
(4150)</td></tr>
<tr><td>76-A-36
76-A-37
76-A-38</td><td>(3)</td><td>(3)</td><td>25
25
25</td><td>(1.0)
(1.0)
(1.0)</td><td>17800
18250
17000</td><td>(4000)
(4100)
(4000)</td></tr>
</table>

(1) Base metal failure, however, since the nugget diameter 7.1mm (0.28-inch) is equal for all specimens listed in this Table; the lap-shear strength is considered to be equal for all specimens.

(2) An overlap of 19mm (0.75-inch) was used for these specimens.

(3) Individual blanks and single spot welds were used for these specimens.

Spot Weld Schedules for Ti-6Al-4V

Most aircraft component joints are made from parts having different thicknesses; therefore, spot-weld schedules were established for different two-layer, three-layer, and four-layer combinations using the following sheet thicknesses: 0.5 mm (0.020 inch), 1.0 mm (0.040 inch), and 1.6 mm (0.063 inch).

For each joint-thickness combination selected, the lap-shear strength was determined as a function of welding current. The welding current was measured with a (Duffer's) secondary current meter. Other variables included electrode force and welding times (number of heat cycles). Nugget diameter (surface measurements), surface electrode indentation and joint gap was determined for each set of welding parameters.

The results of this welding parameter investigation are presented in Figures 6 through 22. Nine different material thickness combinations are represented in these Figures. For thin sheet thickness lower welding currents are used to produce class A welds than that required for thick sheet joint combinations. For each thickness combination, the lap-shear strength as a function of welding current is shown on the left page. The corresponding spot weld microstructure is shown on the right page. An attempt was made to have the spot weld microstructures represent the low welding current and the high welding current used to obtain the lap-shear strength data. However, in some cases it was also desirable to learn what effect slightly higher welding currents would have on the microstructure of spot welds. This information would be valuable in determining spot weld schedules which would provide class A welds and still provide a wide range of welding currents so that high quality welds would be easy to obtain in a manufacturing operation.

A change in welding current has the most significant effect on lap-shear strength. By increasing the percent heat setting in the single phase resistance spot welding machine the welding current is increased. Also, by increasing the number of heat cycles for a given heat setting there will be a slight increase in welding current. An increase in electrode force also results in a slight increase in lap-shear strength as seen in Figure 8 and in Figure 12. In general, the electrode force is not a critical variable.

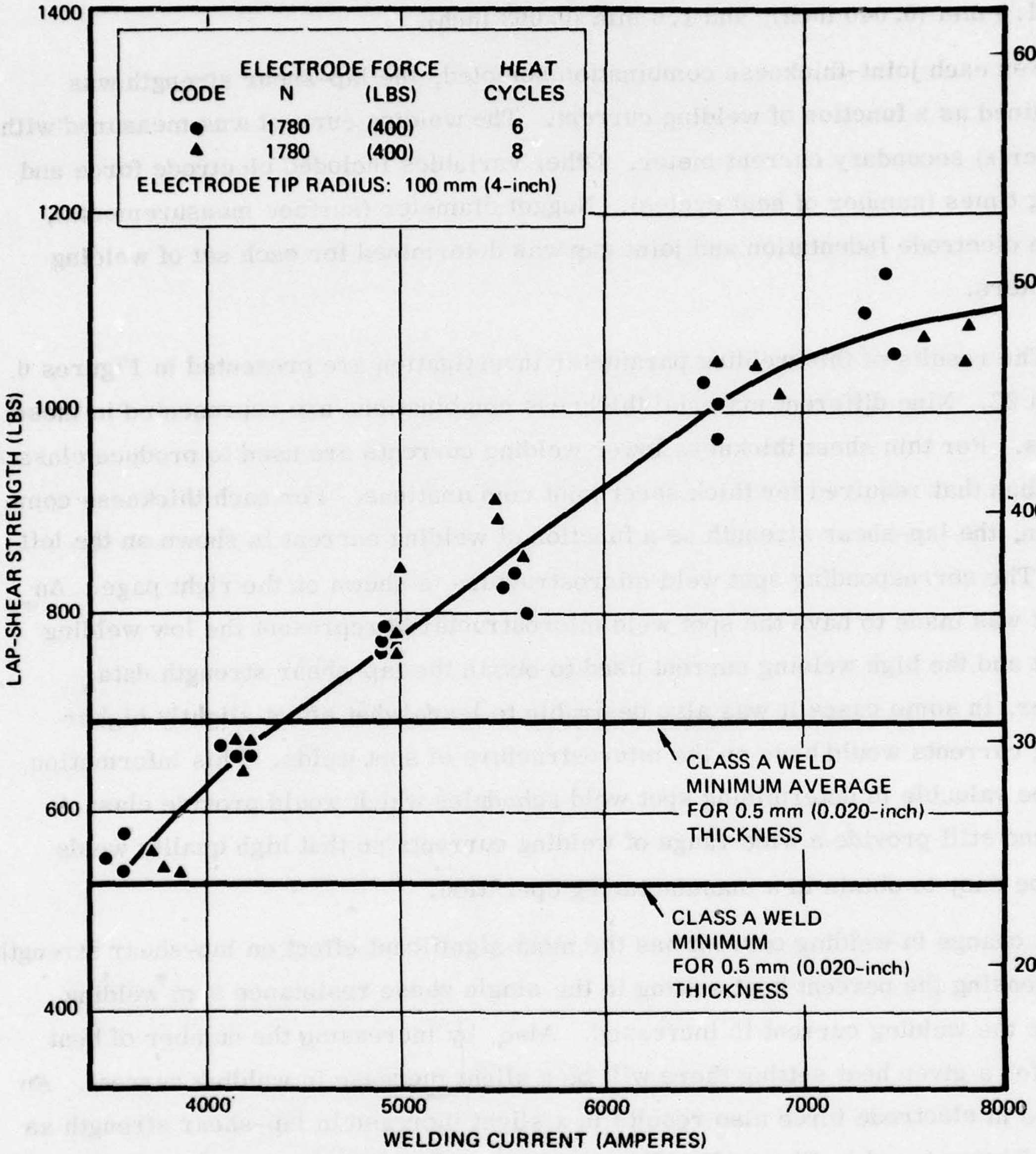
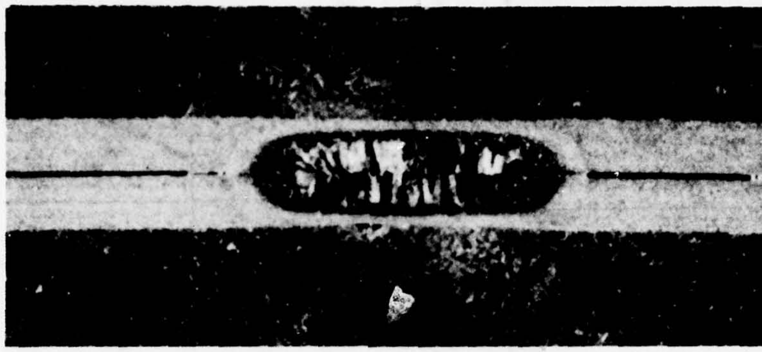
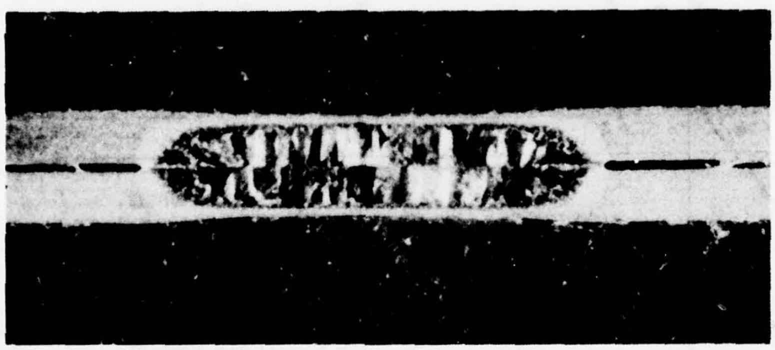


FIGURE 6. EFFECT OF WELDING PARAMETERS ON LAP-SHEAR STRENGTH FOR Ti-6A1-4V, 0.5 to 0.5 mm (0.020 to 0.020-inch)



13X

WELDING CURRENT: 5600 AMPERES
HEAT CYCLES: 6
ELECTRODE FORCE: 1780 N (400 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)



13X

WELDING CURRENT: 8100 AMPERES
HEAT CYCLES: 8
ELECTRODE FORCE: 1780 N (400 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 7. SPOT WELD MICROSTRUCTURE FOR Ti-6Al-4V, 0.5 to 0.5 mm (0.020 to 0.020-inch)

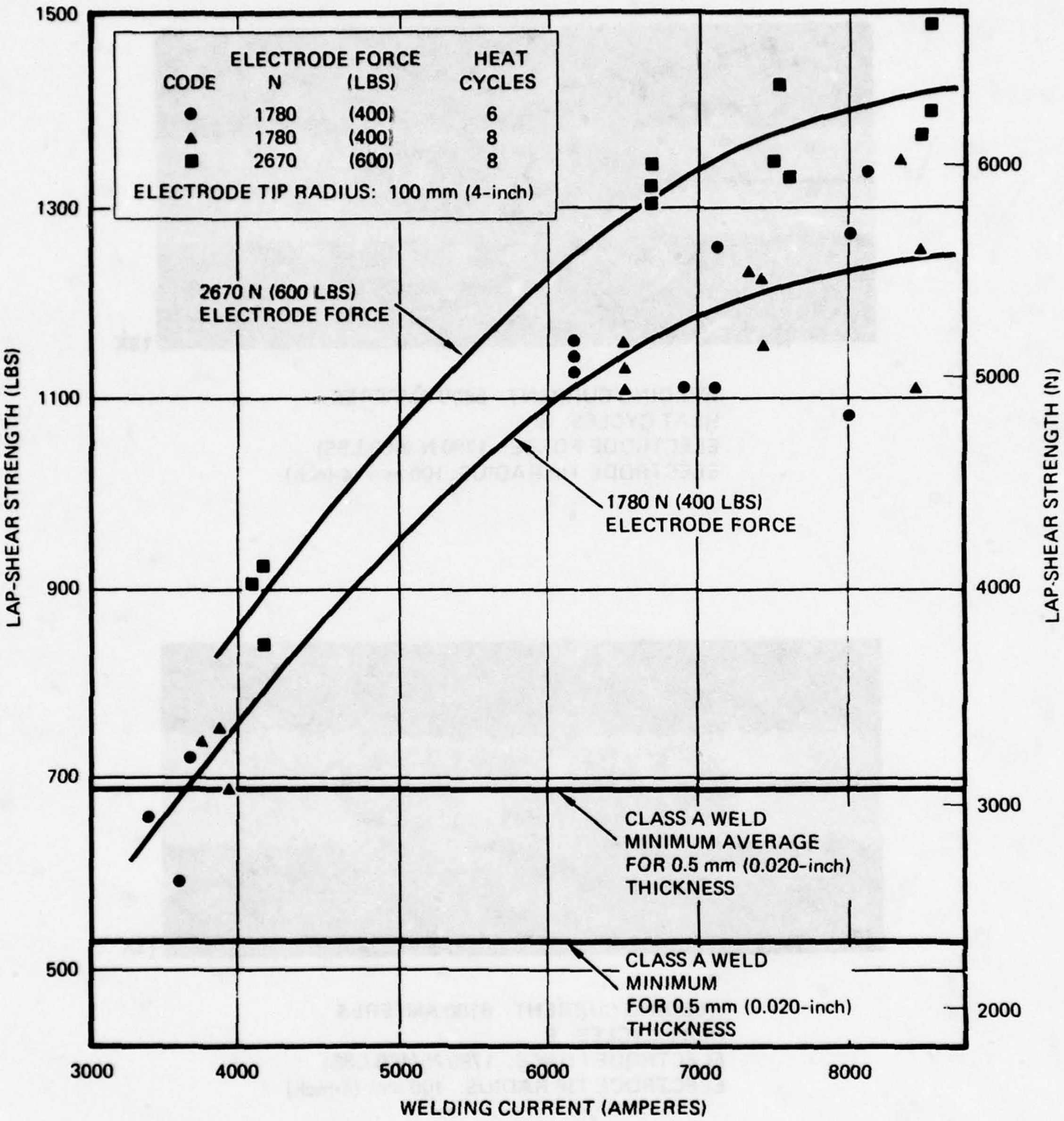
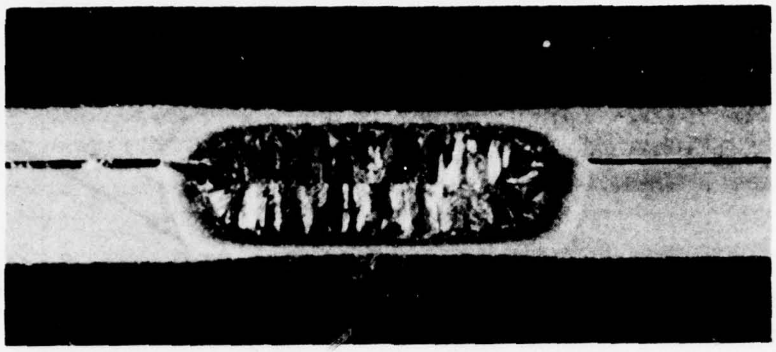


FIGURE 8. EFFECT OF WELDING PARAMETERS ON LAP-SHEAR STRENGTH FOR Ti-6Al-4V, 0.5 to 1.0 mm (0.020 to 0.040-inch)



WELDING CURRENT: 6600 AMPERES
HEAT CYCLES: 6
ELECTRODE FORCE: 1780 N (400 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

WELDING CURRENT: 9800 AMPERES
HEAT CYCLES: 8
ELECTRODE FORCE: 2670 N (600 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 9. SPOT WELD MICROSTRUCTURE FOR Ti-6Al-4V, 0.5 to 1.0 mm (0.020 to 0.040-inch)

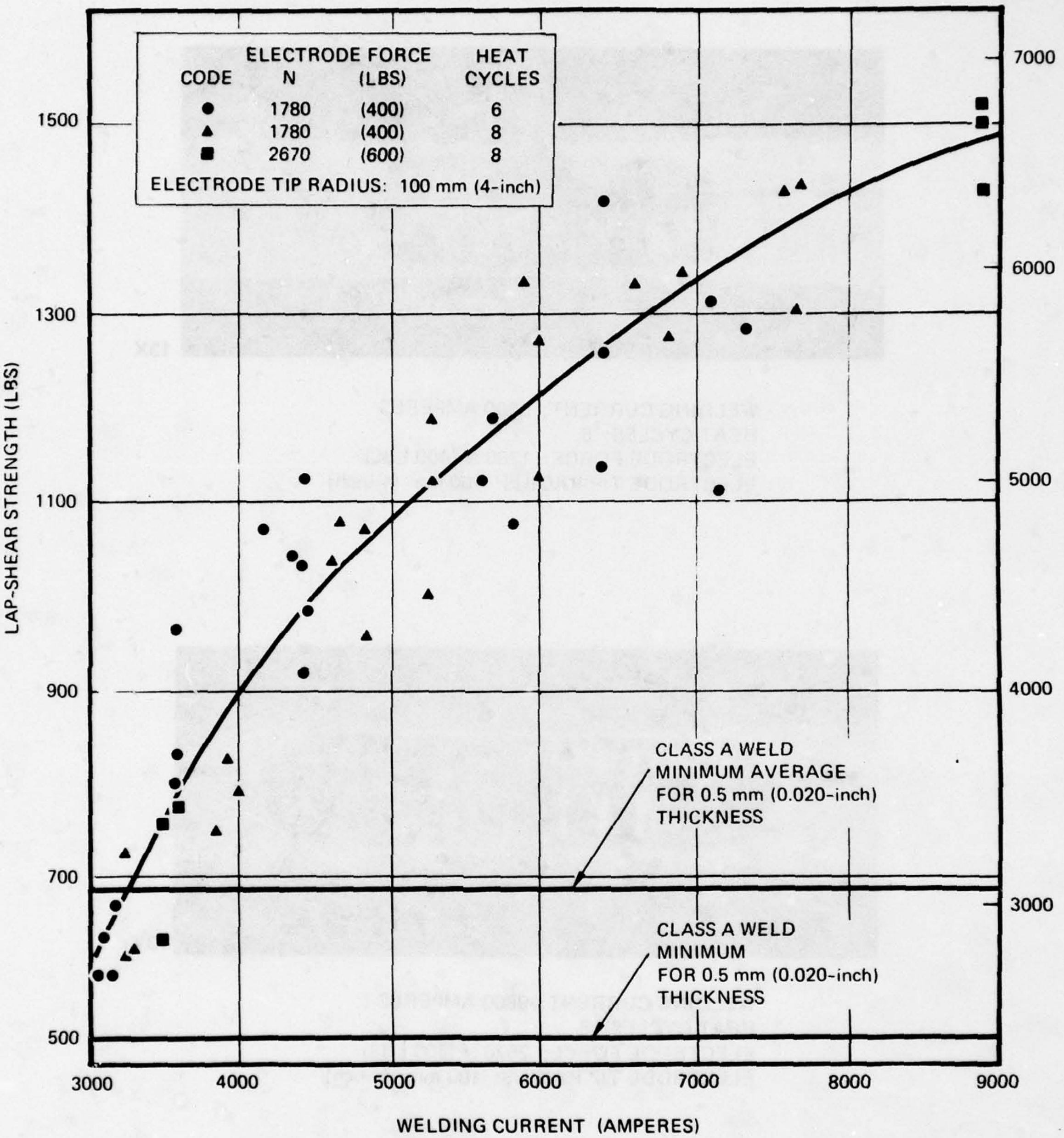
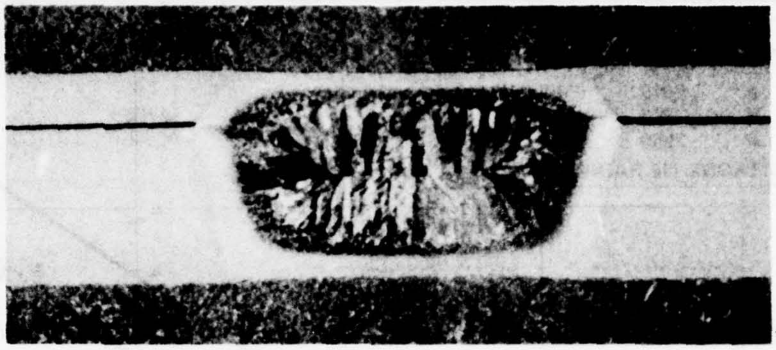
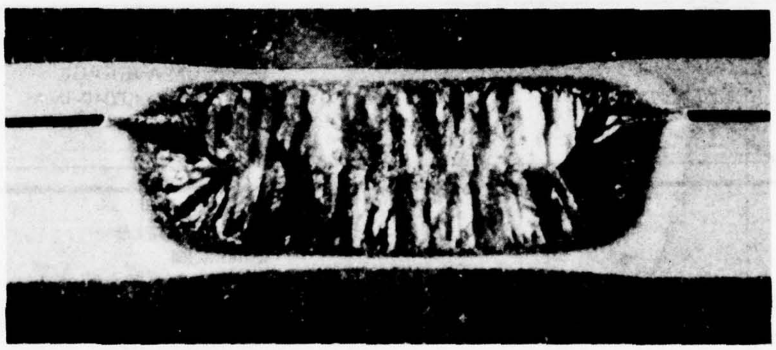


FIGURE 10. EFFECT OF WELDING PARAMETERS ON LAP-SHEAR STRENGTH FOR Ti-6Al-4V, 0.5 to 1.6 mm (0.020 to 0.063-inch)



WELDING CURRENT: 5800 AMPERES
HEAT CYCLES: 6
ELECTRODE FORCE: 1780 N (400 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)



WELDING CURRENT: 9500 AMPERES
HEAT CYCLES: 8
ELECTRODE FORCE: 2670 N (600 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 11. SPOT WELD MICROSTRUCTURE FOR Ti-6Al-4V, 0.5 to 1.6 mm (0.020 to 0.063-inch)

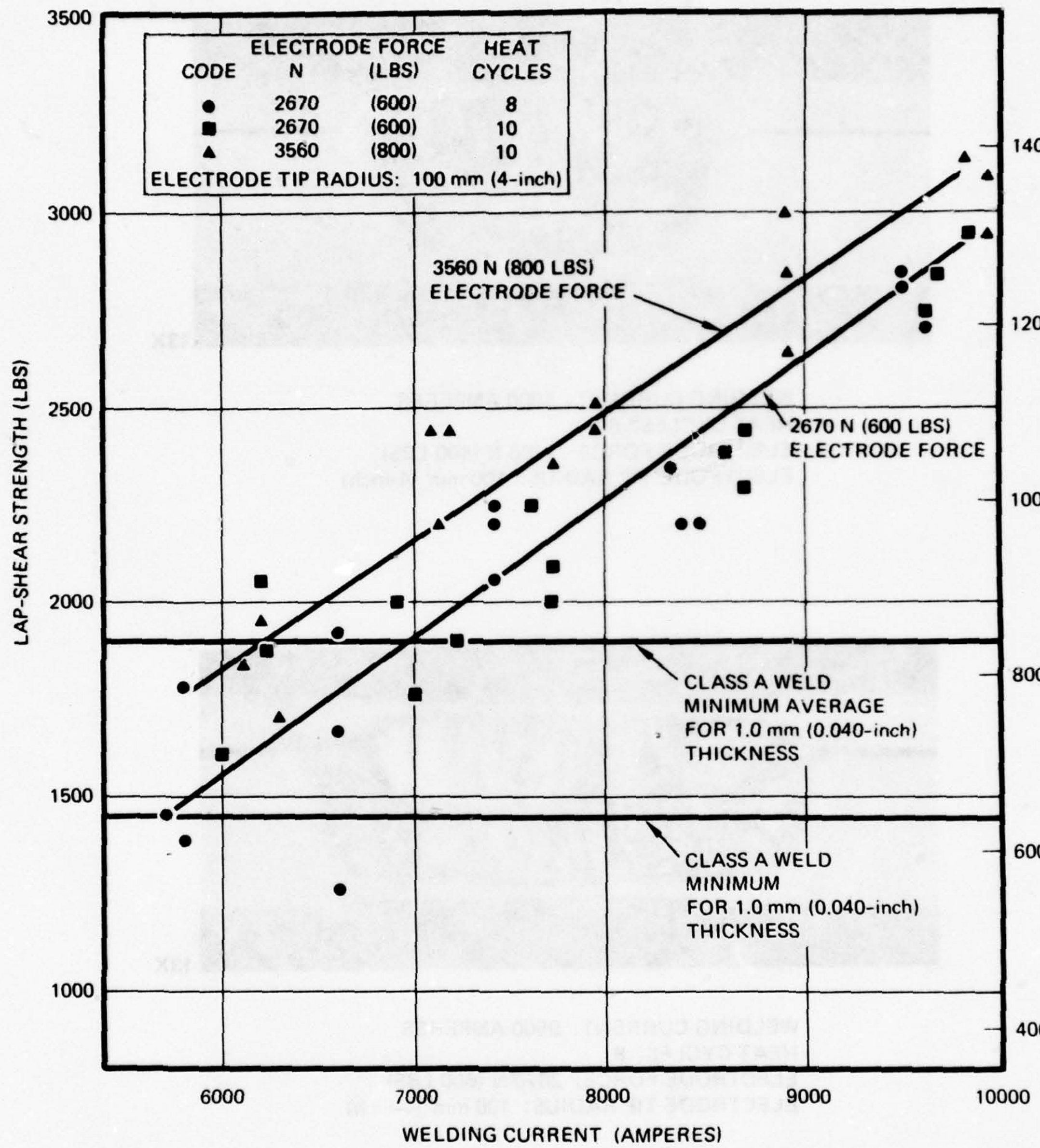
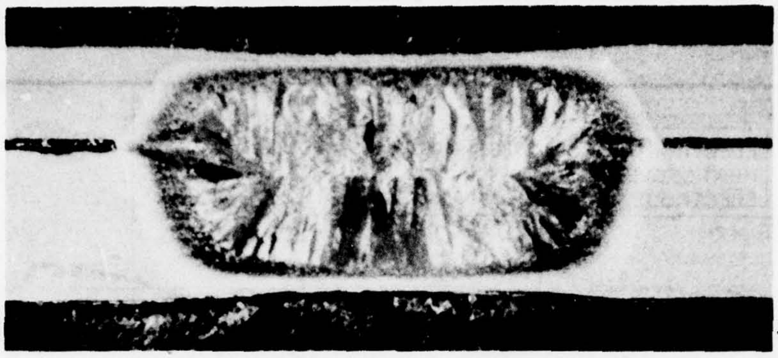


FIGURE 12. EFFECT OF WELDING PARAMETERS ON LAP-SHEAR STRENGTH FOR Ti-6Al-4V, 1.0 to 1.6 mm (0.040 to 0.063-inch)



13X

WELDING CURRENT: 7400 AMPERES
HEAT CYCLES: 8
ELECTRODE FORCE: 2670 N (600 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

13X

WELDING CURRENT: 9900 AMPERES
HEAT CYCLES: 10
ELECTRODE FORCE: 3560 N (800 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 13. SPOT WELD MICROSTRUCTURE FOR Ti-6A1-4V, 1.0 to 1.6 mm (0.040 to 0.063-inch)

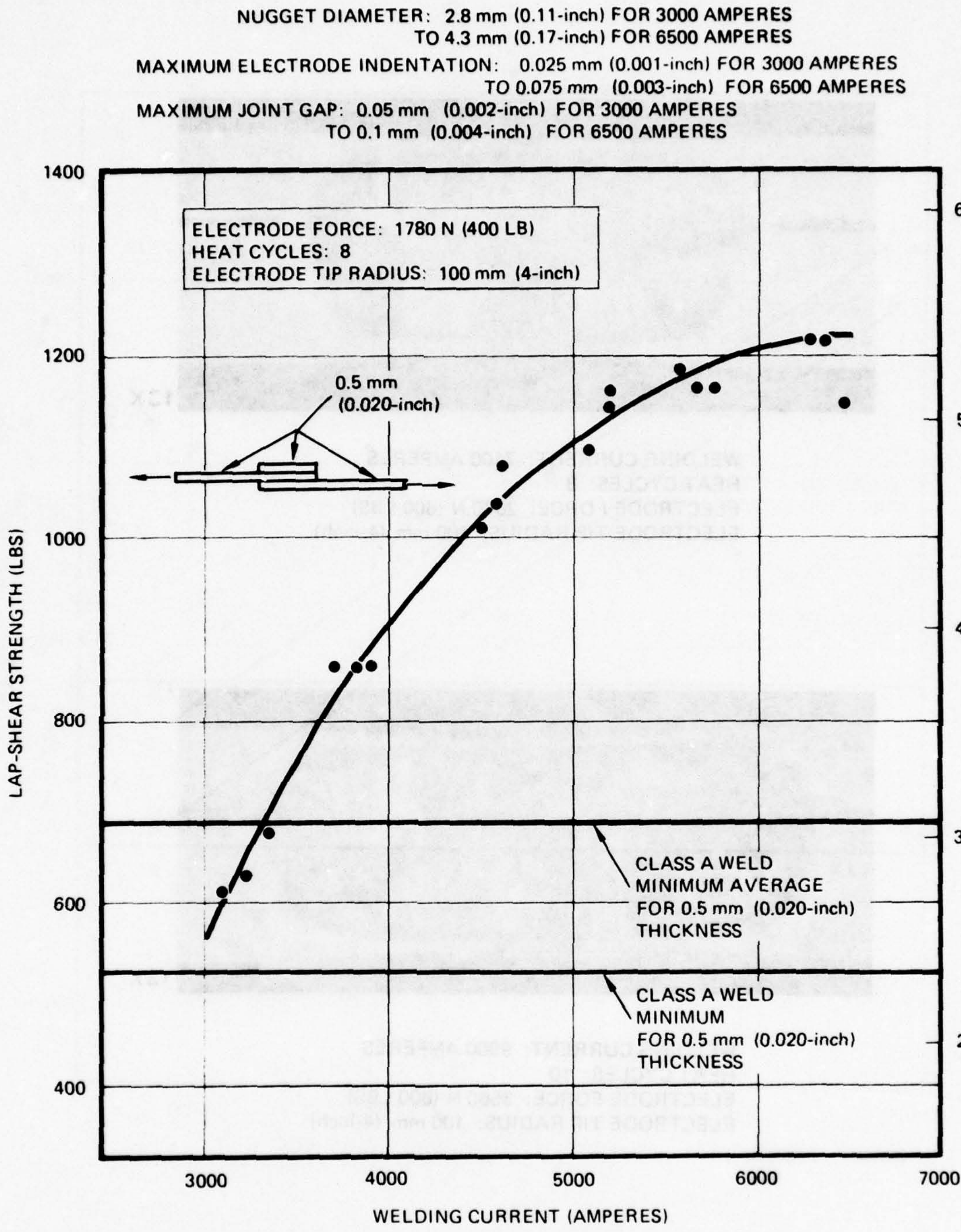
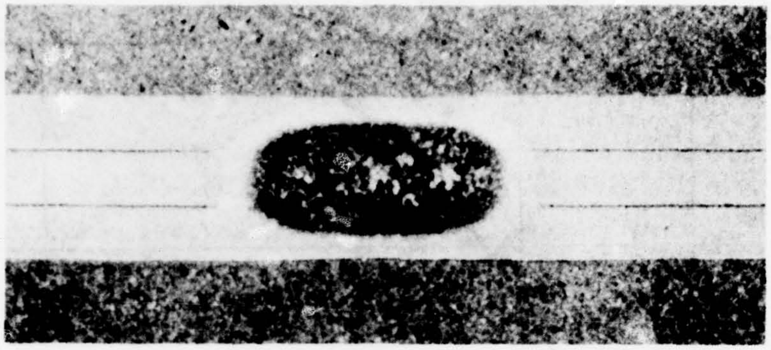
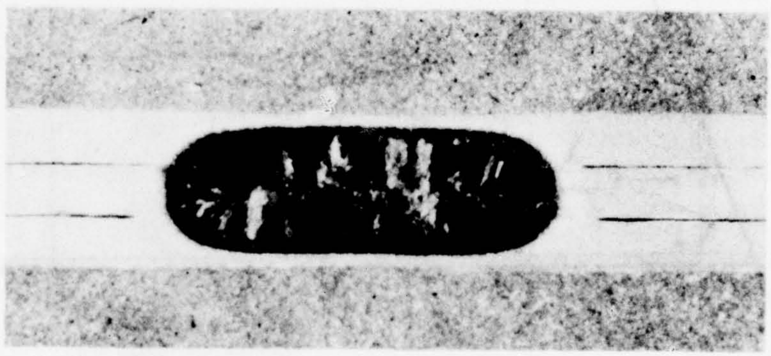


FIGURE 14. EFFECT OF WELDING CURRENT ON SPOT WELD PROPERTIES FOR Ti-6Al-4V, 0.5/0.5/0.5 mm (0.020/0.020/0.020-inch)



13X

WELDING CURRENT: 3550 AMPERES
HEAT CYCLES: 8
ELECTRODE FORCE: 1780 N (400 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)



13X

WELDING CURRENT: 6100 AMPERES
HEAT CYCLES: 8
ELECTRODE FORCE: 1780 N (400 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 15. SPOT WELD MICROSTRUCTURE FOR Ti-6Al-4V, 0.5/0.5/0.5 mm (0.020/0.020/0.020-inch)

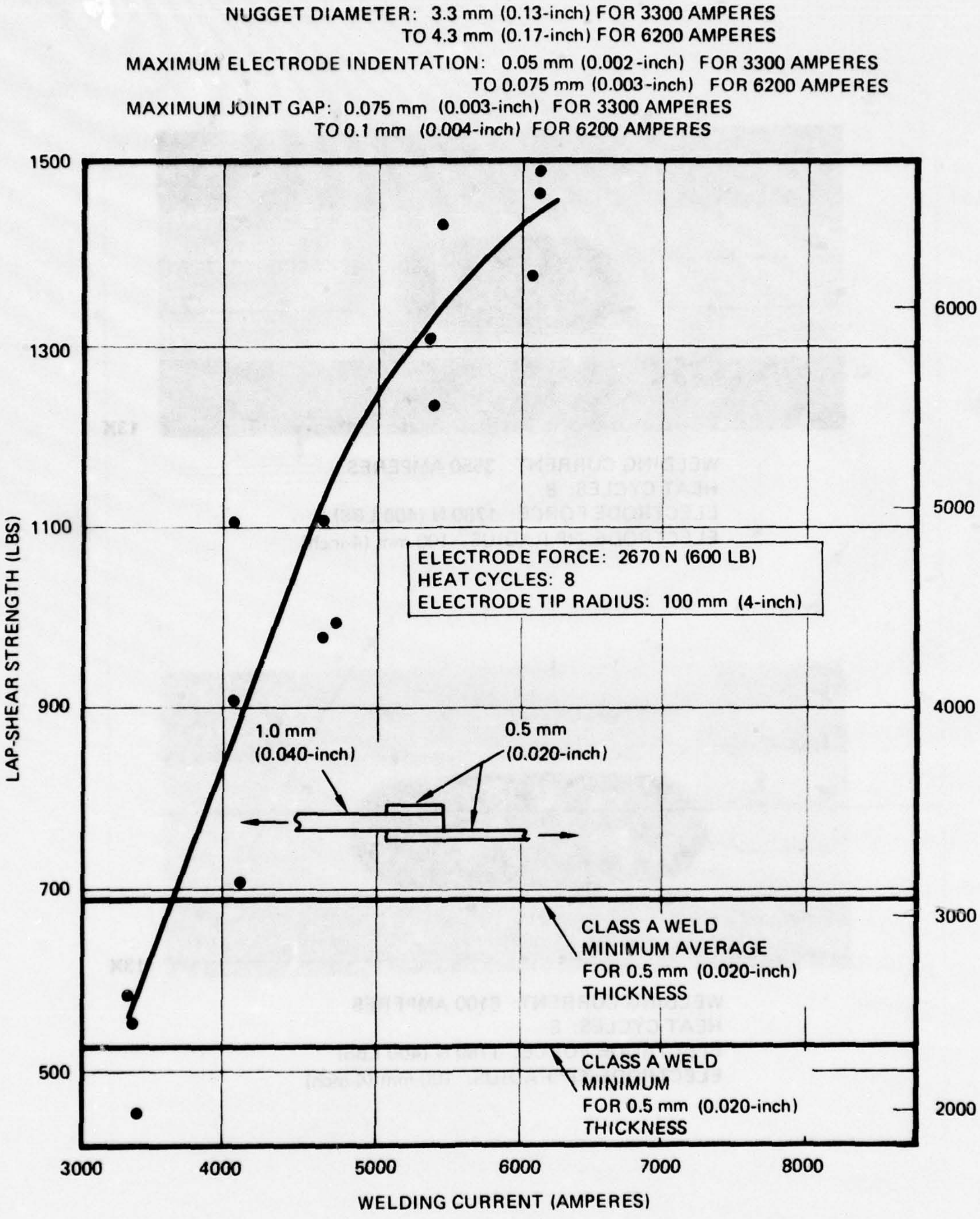
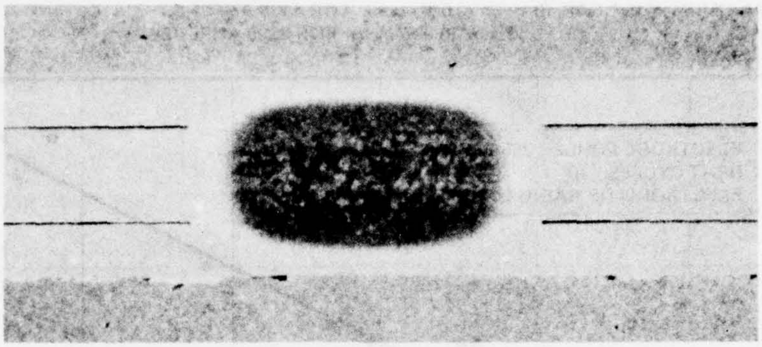
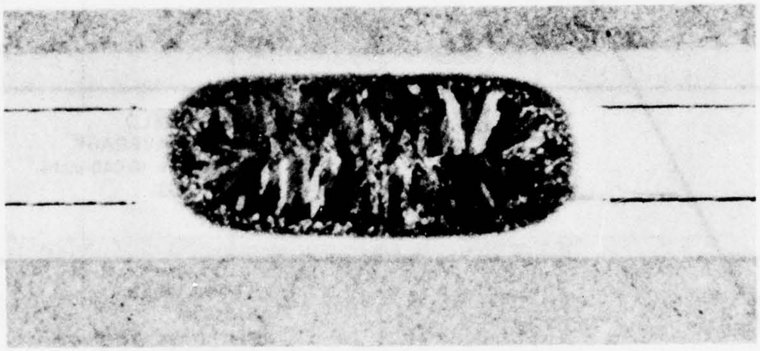


FIGURE 16. EFFECT OF WELDING CURRENT ON SPOT WELD PROPERTIES FOR Ti-6Al-4V, 0.5/1.0/0.5 mm (0.020/0.040/0.020-inch)



13X

WELDING CURRENT: 4300 AMPERES
HEAT CYCLES: 8
ELECTRODE FORCE: 2670 N (600 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)



13X

WELDING CURRENT: 6200 AMPERES
HEAT CYCLES: 8
ELECTRODE FORCE: 2670 N (600 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 17. SPOT WELD MICROSTRUCTURE FOR Ti-6Al-4V, 0.5/1.0/0.5 mm (0.020/0.040/0.020-inch)

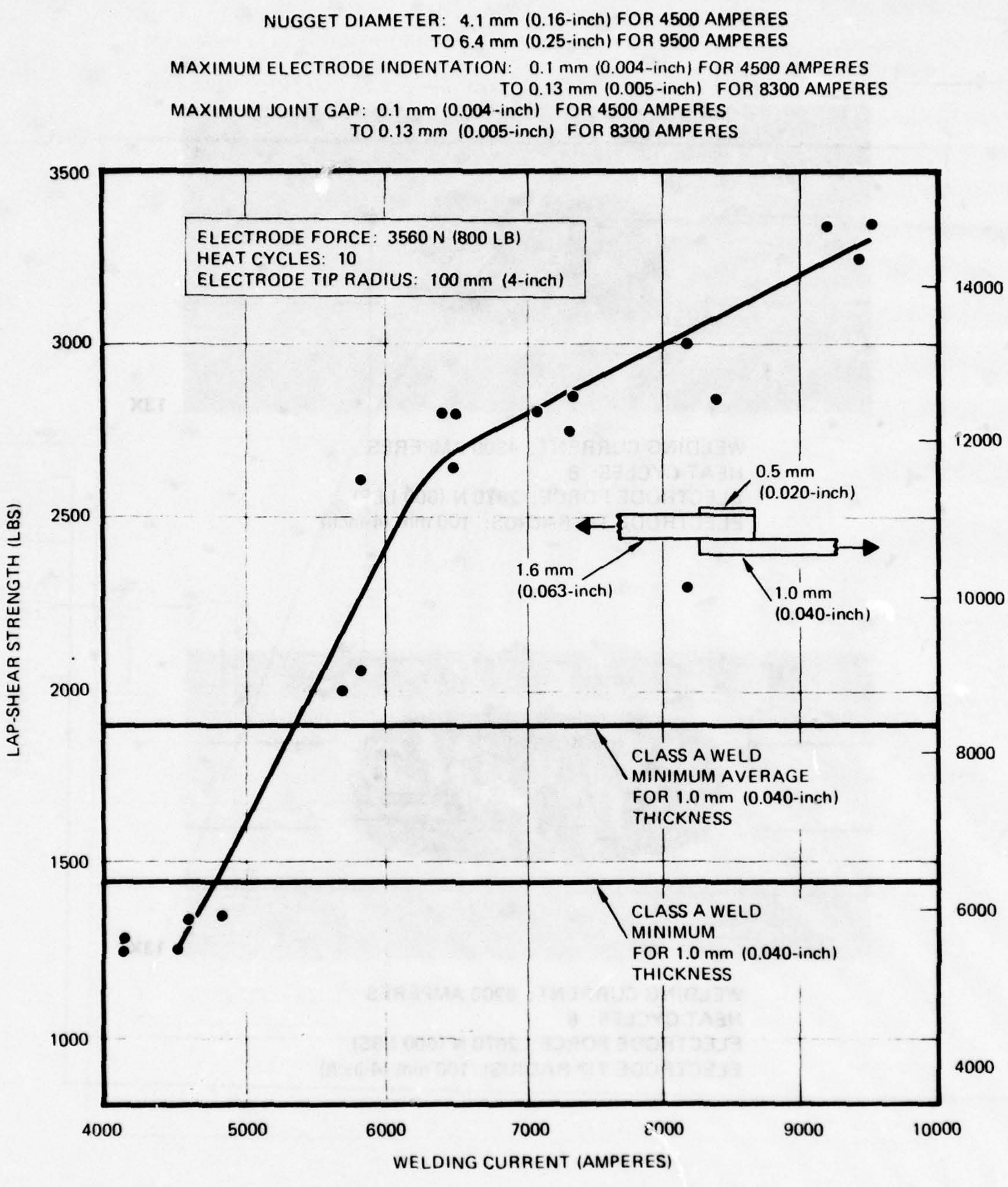
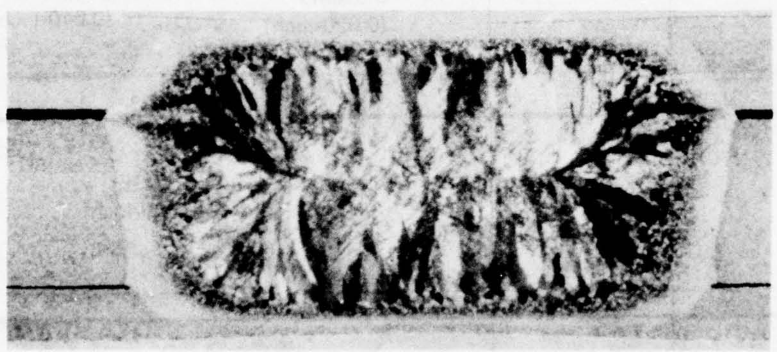


FIGURE 18. EFFECT OF WELDING CURRENT ON SPOT WELD PROPERTIES FOR Ti-6Al-4V, 1.0/1.6/0.5 mm (0.040/0.063/0.020-inch)

13X

WELDING CURRENT: 6000 AMPERES
HEAT CYCLES: 10
ELECTRODE FORCE: 3560 N (800 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)



13X

WELDING CURRENT: 8400 AMPERES
HEAT CYCLES: 10
ELECTRODE FORCE: 3560 N (800 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 19. SPOT WELD MICROSTRUCTURE FOR Ti-6Al-4V, 1.0/1.6/0.5 mm (0.040/0.063/0.020-inch)

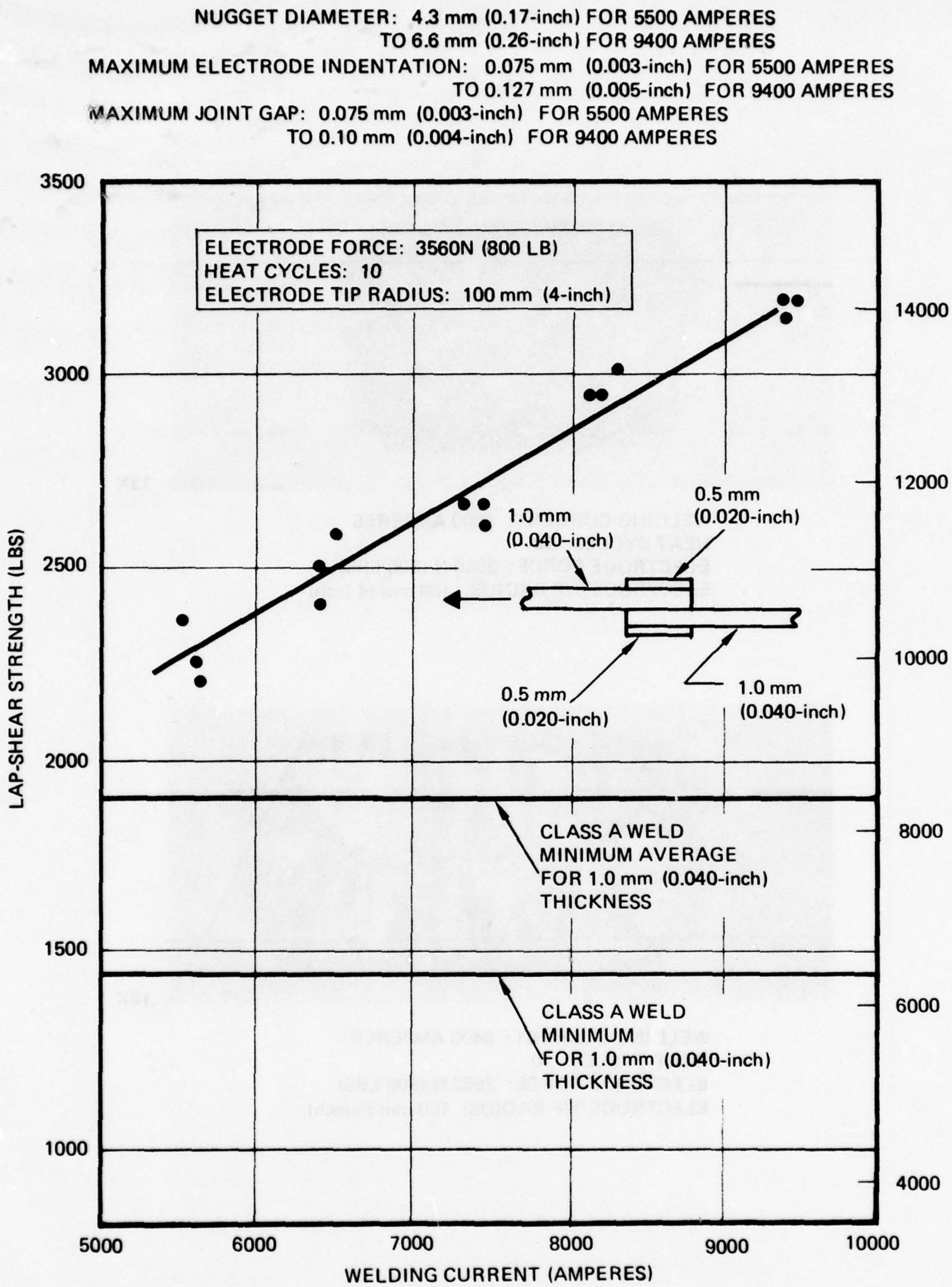
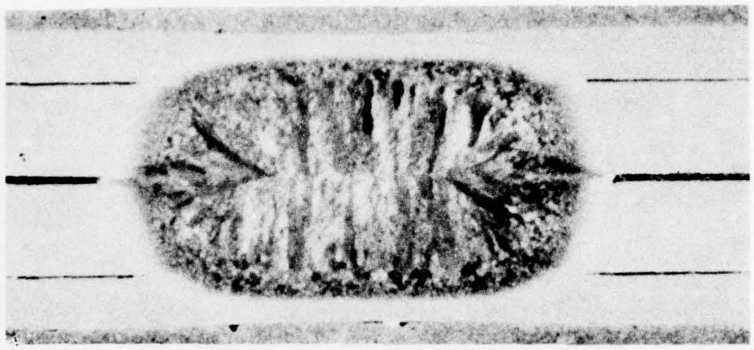
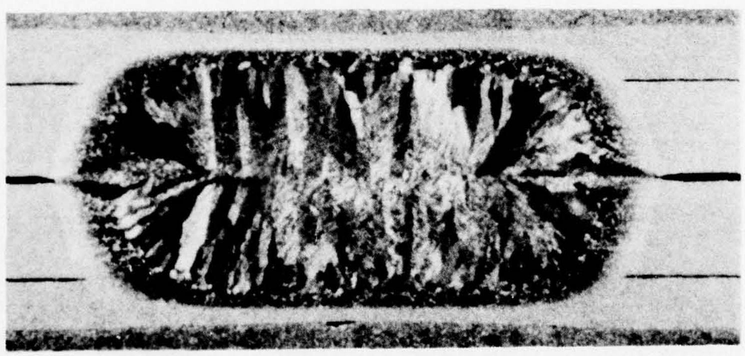


FIGURE 20. EFFECT OF WELDING CURRENT ON SPOT WELD PROPERTIES FOR Ti-6A1-4V, 0.5/1.0/1.0/0.5 mm (0.020/0.040/0.040/0.020-inch)



13X

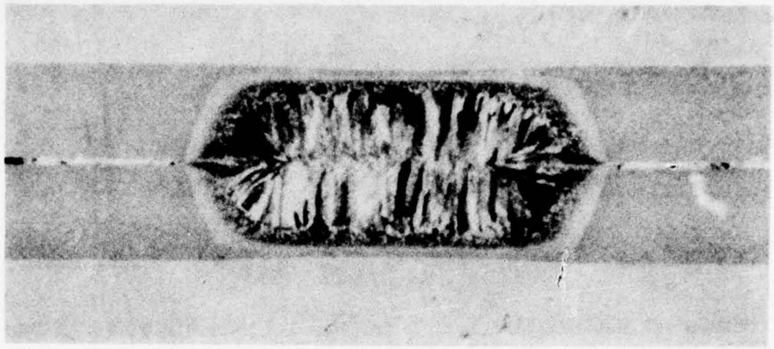
WELDING CURRENT: 6100 AMPERES
HEAT CYCLES: 10
ELECTRODE FORCE: 3560 N (800 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)



13X

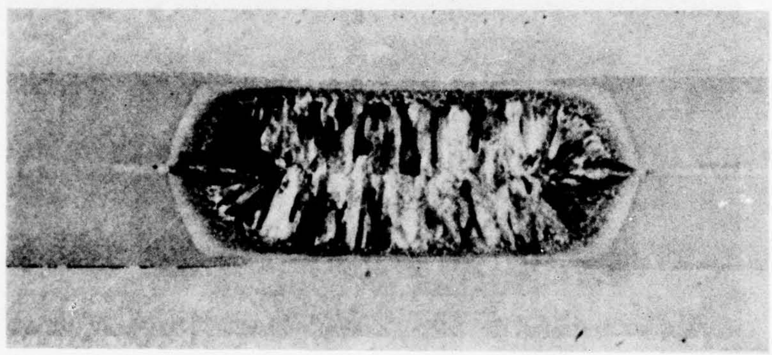
WELDING CURRENT: 8100 AMPERES
HEAT CYCLES: 10
ELECTRODE FORCE: 3560 N (800 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 21. SPOT WELD MICROSTRUCTURE FOR Ti-6Al-4V, 0.5/1.0/1.0/0.5 mm (0.020/0.040/0.040/0.020-inch)



7.5X

WELDING CURRENT: 10,000 AMPERES
HEAT CYCLES: 12
ELECTRODE FORCE: 5340 N (1200 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)



7.5X

WELDING CURRENT: 11,800 AMPERES
HEAT CYCLES: 12
ELECTRODE FORCE: 5340 N (1200 LBS)
ELECTRODE TIP RADIUS: 100 mm (4-inch)

FIGURE 22. SPOT WELD MICROSTRUCTURE FOR Ti-6Al-4V, 1.6 to 1.6 mm (0.063 to 0.063-inch)

Based on the data presented in Figures 6 through 22, and on metallographic analyses of the spot welds, recommended spot welding schedules were established for these joint thickness conbinations as shown in Table 5. Factors which were taken into consideration included lap-shear strength, sheet separation to allow successful filler metal flow, and other criteria required for class A welds as defined in MIL-W-6858C. Radiographic inspection and metallographic inspection revealed no porosity or internal defects in spot welds made with the low and high welding current for each thickness combination shown in Table 5. The results of the metallographic examination for low and high welding currents is presented in Table 6. It can be seen that for low and high welding currents, class A welds are obtained in terms of nugget penetration, maximum sheet separation, nugget diameter, and maximum surface indentation. All welds made to the welding schedules shown in Table 5 easily meet the requirements for Class A welds in accordance with *MIL-W-6858C.*

An additional study was made with respect to weld nugget diameter measurements. It was determined that nugget diameters, which were measured on the surface of the lap joint by measuring the indentation (or discoloration) diameters, gave dimensions which were within 5% of the value obtained by metallographic examination. Since there is a correlation between nugget diameter and lap-shear strength (i.e. Table 6 and corresponding figures) the lap-shear strength of the welds could be determined non-destructively in critical joints by measuring the nugget diameter at the surface of the joint.

Within the recommended current range given in Table 5, the electrode force can be varied plus or minus 25% of the single values shown in Table 5 and still obtain high strength, Class A welds. This latitude in electrode force allows more force to be used for aircraft component joints which exhibit uneven fit up due to tolerance variations.

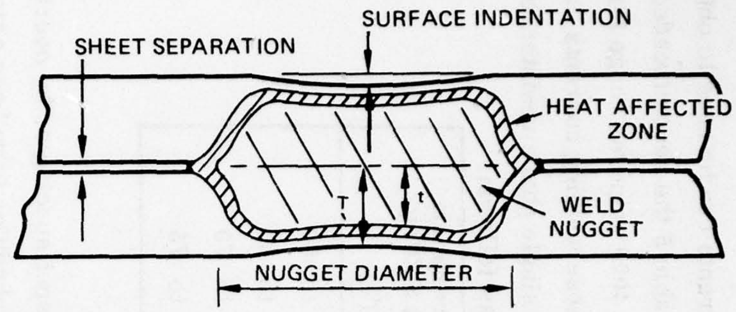
TABLE 5. RECOMMENDED SPOT WELDING SCHEDULES FOR CLASS A WELDS IN Ti-6Al-4V

Class 2 or Class 3 electrode with a 100mm (4-inch) tip radius

THICKNESS COMBINATION NO.	WELDING CURRENT (AMPERES)	HEAT CYCLES	ELECTRODE FORCE N	ELECTRODE FORCE (LBS)
1. 0.5 to 0.5mm (0.020 to 0.020-inch)	5000 to 8000	6 to 8	1780	(400)
2. 0.5 to 1.0mm (0.020 to 0.040-inch)	4000 to 8000	6 to 8	1780 to 2670	(400 to 600)
3. 0.5 to 1.6mm (0.020 to 0.063-inch)	4000 to 8000	6 to 8	1780 to 2670	(400 to 600)
4. 1.0 to 1.6mm (0.040 to 0.063-inch)	7000 to 9000	8 to 10	2670 to 3560	(600 to 800)
5.* 1.6 to 1.6mm (0.063 to 0.063-inch)	10000 to 12000	12	5340 to 6230	(1200 to 1400)
6. 0.5 to 0.5 to 0.5mm (0.020 to 0.020 to 0.020-inch)	4000 to 6000	8	1780	(400)
7. 0.5 to 1.0 to 0.5mm (0.020 to 0.040 to 0.020-inch)	4000 to 6000	8	2670	(600)
8. 1.0 to 1.6 to 0.5mm (0.040 to 0.063 to 0.020-inch)	6000 to 8500	10	3560	(800)
9. 0.5 to 1.0 to 1.0 to 0.5mm (0.020 to 0.040 to 0.040 to 0.020-inch)	6000 to 8000	10	3560	(800)

*Electrode tip radius of 150mm (6-inch) recommended for minimum surface indentation

TABLE 6. SPOT WELD CHARACTERISTICS DETERMINED BY METALLOGRAPHIC EXAMINATION FOR LOW AND HIGH WELDING CURRENTS, Ti-6Al-4V



PERCENT NUGGET PENETRATION $\frac{t}{T}$ X 100

SHEET THICKNESS mm (inch)	WELDING CURRENT (AMPERES)	PENETRATION* TOP/BOTTOM (%)	MAXIMUM SHEET SEPARATION* mm (inch)	NUGGET DIAMETER* mm (inch)	MAXIMUM SURFACE INDENTATION* mm (inch)
0.5/0.5 (0.020/0.020)	5,600 8,100	80/75 86/83	0.05 (0.0020) 0.08 (0.0030)	3.30 (0.130) 4.88 (0.192)	0.05 (0.002) 0.08 (0.003)
0.5/1.0 (0.020/0.040)	6,600 9,800	72/88 86/91	0.08 (0.0030) 0.15 (0.0060)	4.19 (0.165) 5.87 (0.231)	0.08 (0.003) 0.13 (0.005)
0.5/1.6 (0.020/0.063)	5,800 9,500	64/86 76/91	0.06 (0.0025) 0.10 (0.0040)	4.19 (0.165) 5.87 (0.231)	0.05 (0.002) 0.13 (0.005)
1.0/1.6 (0.040/0.063)	7,400 9,900	88/90 88/90	0.11 (0.0045) 0.15 (0.0060)	5.46 (0.215) 6.86 (0.270)	0.10 (0.004) 0.13 (0.005)
1.6/1.6 (0.063/0.063)	10,000 11,800	88/88 90/90	0.13 (0.005) 0.15 (0.006)	7.4 (0.29) 8.3 (0.33)	0.13 (0.005) 0.13 (0.005)
0.5/0.5/0.5 (0.020/0.020/0.020)	3,550 6,100	50/50 75/73	0.013 (0.0005) 0.03 (0.0010)	2.5 (0.10) 4.1 (0.16)	0.03 (0.001) 0.05 (0.002)
0.5/1.0/0.5 (0.020/0.040/0.020)	4,300 6,200	45/45 65/65	0.03 (0.001) 0.05 (0.002)	2.8 (0.11) 4.3 (0.17)	0.03 (0.001) 0.05 (0.002)
1.0/1.6/0.5 (0.040/0.063/0.020)	6,000 8,400	75/45 80/65	0.05 (0.002) 0.08 (0.003)	4.6 (0.18) 6.1 (0.24)	0.05 (0.002) 0.10 (0.004)
0.5/1.0/1.0/0.5 (0.020/0.040/0.040/0.020)	6,100 8,100	50/50 86/87	0.08 (0.003) 0.10 (0.004)	4.9 (0.19) 6.1 (0.24)	0.08 (0.003) 0.08 (0.003)

*CLASS A WELD REQUIREMENTS PER MIL-W-6858C:

PENETRATION: 20% MINIMUM TO 90% MAXIMUM
SHEET SEPARATION: 0.15 mm (0.006-inch) MAXIMUM
NUGGET DIAMETER (MINIMUM): 2.5 mm (0.10-inch) FOR 0.5 mm (0.020-inch) SHEET
4.0 mm (0.16-inch) FOR 1.0 mm (0.040-inch) SHEET
5.1 mm (0.20-inch) FOR 1.6 mm (0.063-inch) SHEET
SURFACE INDENTATION (MAXIMUM): 10% SHEET THICKNESS OR 0.13 mm (0.005-inch), WHICHEVER IS GREATER

Also, it can be seen that a large range of welding currents can be used to obtain Class A welds. For the thickness combinations shown in Table 5 the recommended welding current ranges allow a 2000 amperes range up to a 4000 amperes range for some joint thickness combinations. To show how readily these welding currents can be obtained, the corresponding percent heat settings on the single phase resistance spot welding machine used for this program are presented as follows:

Welding Current (Amperes)	Approximate Heat Setting (%)
4,000 to 6,000	30 to 50
6,000 to 8,000	50 to 60
8,000 to 10,000	60 to 70
10,000 to 12,000	70 to 75

Spot Weld Parameter Summary

Spot weld lap shear strength is not affected either by spot spacing or by overlap distances within the broad ranges investigated. Spot weld schedules have been established for nine joint thickness combinations. The broad range of spot weld parameters permitted by the welding schedules shown in Table 5 will permit low cost, easy to control manufacturing procedures that will produce spot welds of consistently high quality. The low electrode force makes feasible the adaptation of extension arms to a resistance spot welding machine to be used for spot welding areas where access is difficult. The resulting lap-shear strength is high and the sheet separation should allow excellent braze filler metal flow for weldbraze joints in airframe components. Many of the joint thicknesses combinations shown in Table 5 have similar weld schedules; therefore, extrapolation of these schedules for other thickness combinations can easily be made.

BRAZING PROCEDURES

The objective of this portion of the program was to establish an optimum brazing environment and to conduct screening tests for several filler metals. Methods for placing the filler metal at the edge of the joint were evaluated and vertical flow weldbraze joints were evaluated.

Brazing Environment

Studies made during this program have shown that brazing in a partial pressure of argon results in better filleting of the filler metal than is obtained from brazing in a vacuum. Also, it has been determined that better filler metal flow is obtained when a titanium foil shield or cover is placed around the lap joint to act as a getter for any contamination that might exist in the furnace or brazing environment. An optimum brazing cycle is as follows: heat the part in a vacuum to 590K (600F), backfill with argon to a partial pressure of 40 kPa (300 torr), and then heat to the braze temperature, hold for five minutes and furnace cool below 590K (600F) before flowing argon gas for rapid cooling.

All weldbraze specimens used to determine mechanical properties and corrosion resistance for this program were brazed according to the procedure described above. The specimens were heated to the maximum temperature in approximately 50 minutes, to simulate a production cycle, and were furnace cooled to room temperature in one-half hour to one and one-half hours, depending on the size of the furnace load.

Filler-Metal Screening Tests

Screening tests were conducted for five filler-metals in terms of joint appearance, braze temperature, lap-shear strength, and resistance to salt fog corrosion.

Most current aircraft structures being considered for weldbraze joining are designed with annealed Ti-6Al-4V. Brazing temperatures much in excess of 950K (1250F) will allow the titanium to creep, thus eliminating the advantage of a self-supported spotwelded structure. Because of their low melting characteristics, i.e., less than 950K (1250F), aluminum-base filler metals were evaluated for this program. Some of these filler metals contain rare earth additions and melt at 855K (1080F). One of these low melting filler metals, Amdry 389, was evaluated for this program. Since the brazing temperature for most aluminum-base filler metals is approximately 922K (1200F), Amdry 389 could be of interest for components that may require two

brazing cycles, or as a braze repair filler metal. Also Amdry 389, or similar alloys, could be used to braze solution treated and aged material without significantly reducing properties. A second low melting filler metal, AVCO 48 was also included in the screening test evaluations. The three other screening test filler metals which were selected for the preliminary tests include 2319, 5052, and 1100. The compositions and braze temperatures for all the filler metals discussed in this report are shown in Table 7. The first five alloys, 3003, 4043, 718, 201, and No. 7, were evaluated during prior Northrop weldbraze investigations and provided a baseline reference for the evaluation of the additional aluminum-base filler metals.

Normally, 1% magnesium is included in Amdry 389; however, the modified Amdry 389, which contains no magnesium, was the only material available at the time of the preliminary screening test evaluation.

Flow tests using specimens described in the prior section on "Cleaning Methods" were conducted to determine the braze temperature and the weldbraze joint appearance for the aluminum-base filler metals. Each filler metal was chemically cleaned in a nitric-hydrofluoric solution (% by volume: 49.5 HNO_3, 0.5 HF, and 50 H_2O) agitated with an ultrasonic cleaner. Flow specimens made with alloys 2319, 5052, 1100 and AVCO 48 showed excellent wetting with full fillets. On the other hand, the appearance of the joints made with Amdry 389 (modified) showed slightly less wetting and partial fillets. Also, for both the AVCO 48 alloy and the Amdry 389 alloy, a large amount of oxide layer remained at the edge of the joint, where the filler metal foil had been placed. This condition resulted in a poor weldbraze joint appearance.

After evaluating the flow test specimens, they were subjected to a salt fog exposure for 150 hours (ASTM-B117-73) and then examined for evidence of corrosion. This exposure resulted in only slight corrosion for filler metals 1100 and 5052, and moderate corrosion for filler metals 2319, AVCO 48, and Amdry 389. This indicates that copper additions greater than 1% or additions of tin decreased the corrosion resistance of aluminum/titanium brazements.

Lap-shear specimens were weldbrazed using these five filler metals and then tested at room temperature. The highest weldbraze strengths were obtained with filler metals 1100, 5052, and AVCO 48. Filler metal 2319 had slightly lower lap-shear strength and the Amdry 389 alloy produced a very low lap-shear strength.

TABLE 7. COMPOSITIONS AND FLOW TEMPERATURES OF ALUMINUM-BASED BRAZING FILLER METALS

ALLOY DESIGNATION	SILICON (%)	IRON (%)	COPPER (%)	SILVER (%)	MANGANESE (%)	MAGNESIUM (%)	ZINC (%)	TITANIUM (%)	*FLOW TEMPERATURE ON Ti-6Al-4V	
									°K	°F
3003	0.6	0.7	0.2	---	1.0-1.5	---	0.1	---	945	1240
4043	4.5- 6.0	0.8	0.3	---	0.05	0.05	0.1	---	920	1200
718	11.0-13.0	0.8	0.30	---	0.15	0.10	0.2	---	920	1200
201	0.05	0.1	4.0-5.0	0.4-1.0	0.2-0.35	0.2-0.3	---	0.15-0.35	940	1230
No. 7	---	---	32.0	5.0	---	---	---	---	880	1120
2319 (1)	0.2	0.3	5.8-6.8	---	0.2-0.4	0.02	0.10	0.10-0.20	935	1220
5052 (2)	← 0.45	→	0.10	---	0.1	2.2-2.8	0.10	---	935	1220
1100 (3)	---	---	---	---	---	---	---	---	935	1220
Avco 48	4.8	---	3.8	---	---	---	---	---	890	1140
Amdry 389(4) (Modified)	10.0	---	---	---	---	---	---	---	855	1080

*Brazing Environment: Argon at 40 kPa (300 torr)

(1) Additional elements: Vanadium 0.05-0.15, Zirconium 0.10-0.25

(2) Additional elements: Chromium 0.15-0.35

(3) Aluminum: 99.0 percent minimum

(4) Additional elements: Tin 2.0, Rare Earths 2.0

A summary of the screening tests is presented in Table 8. As a result of this evaluation, three filler metals, 5052, 1100, and AVCO 48 were selected for additional weldbraze property tests which included evaluations of elevated temperature lap-shear strength, cross-tension strength, stress-rupture properties, and stress-corrosion resistance. Alloys 5052 and 1100 were selected for their good corrosion resistance (150-hour salt fog exposure) and high lap-shear strength. To help understand the effects of various alloying elements it was also of interest to evaluate filler metals having significant differences in chemistry. Alloy 5052 has a higher magnesium content than any of the filler metals that were evaluated previously, including 4043, 3003, 718, 201, and No. 7. Alloy 1100 represents a brazing filler metal having the highest purity of all the aluminum filler metals and appears to have good corrosion resistance. Filler metal 2319 (high copper content) was not selected for further evaluation because it produced a low lap-shear strength, 33800N (7600 lbs.) and lower resistance to salt fog exposure (150 hours) compared to filler metals 5052 and 1100. Of the two low brazing temperature filler metals evaluated, AVCO 48 was selected for its high lap-shear strength.

TABLE 8. SCREENING TESTS FOR ALUMINUM ALLOY FILLER METALS

Characteristic \ Filler Metal	1100	5052	2319	AVCO 48	AMDRY 389 (MODIFIED)
Composition (%) Major Alloying Elements	Al 99 (minimum)	Mg. 2.5 Fe } 0.45 Si } Cu 0.1	Mn 0.3 Fe 0.3 Si 0.2 Cu 6.3	Si 4.8 Cu 3.8	Si 10.0 Sn 2.0 Rare Earths 2.0
Braze Temperature °K (°F)	935 (1220)	935 (1220)	935 (1220)	890 (1140)	865 (1100)
Form	Wire	Wire	Wire	Foil	Foil
Availability	Good	Good	Good	Poor	Poor
Weldbraze Joint Appearance	Good	Good	Good	Poor*	Poor*
Weldbraze Lap-Shear Strength	>42200 N >9500 lbs	>42200 N >9500 lbs	33800 N 7600 lbs	>42200 N >9500 lbs	25800 N 5800 lbs
Weldbraze Appearance After 150 hrs Salt Fog	Slight Corrosion	Slight Corrosion	Moderate Corrosion	Moderate Corrosion	Moderate Corrosion

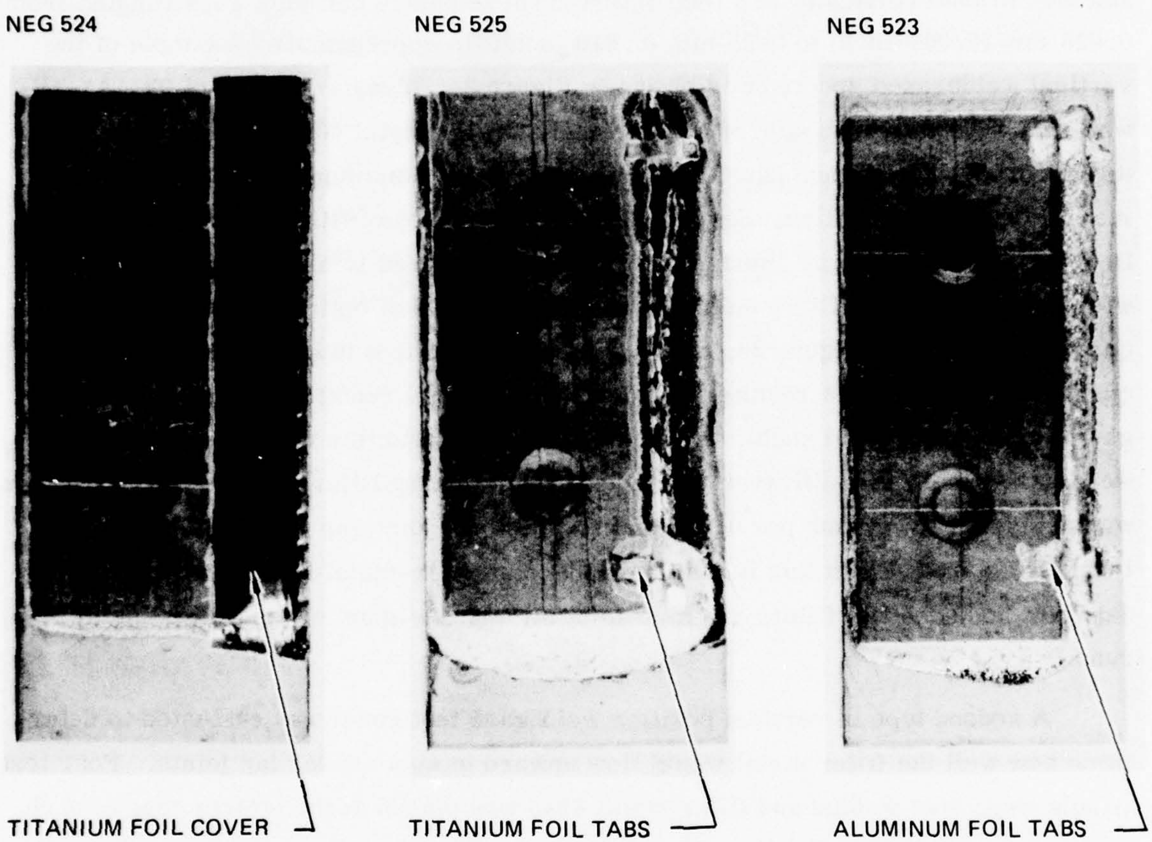
*Oxide or contamination layer from foil remained after braze cycle.

Filler-Metal Placement

Quick, low cost, reliable methods for placing the filler metal along one edge of a lap joint are desirable. In manufacturing large and complicated aircraft structures, some of the lap joints will be in a vertical position during brazing. Therefore, development of methods for holding the filler-metal wire in vertical positions and inverted positions was important.

Attempts to spot weld the aluminum filler-metal wire directly to the titanium failed, due to non-uniform contact which resulted in expulsion. Three other methods were investigated, including a titanium foil cover, titanium foil tabs, and aluminum foil tabs as shown in Figure 23. The titanium foil cover was placed over the filler-metal wire and tack welded to the titanium base metal such that the filler metal was completely enclosed or enapsulated. This method resulted in excellent brazing characteristics. However, it required extensive set-up time and the titanium cover remained at the joint after brazing, creating an undesirable structure. Titanium foil tabs, which reduced the set-up time, were also successful; however the remaining tabs may be undesirable in some areas of a structure.

The best method for obtaining smooth lap-joints utilized aluminum foil tabs which were tack welded to the titanium to hold the filler metal in place along one edge of the lap joint. During the braze cycle the tabs melt and flow into the joint along with the filler metal, leaving the fillet area free of projections. However, spot welded aluminum foil tabs are not as reliable as spot welded titanium tabs, and may shake loose when being loaded into a production furnace, or as a result of furnace vibration during the braze cycle. Judgment must be used for selecting titanium tabs or aluminum tabs based on component appearance requirements and the shape of the part. Either tab method will enable the proper amount of filler metal to be placed at desired locations along the edge of the lap joint and the titanium tabs will maintain filler-metal position for vertical joints, or inverted joints. The amount of time required to place the filler metal and spot weld the aluminum tabs or titanium tabs is comparable to the time required to place filler metal for standard brazing operations.



MAGNIFICATION: 1.5X

FIGURE 23. THREE METHODS FOR PLACING THE FILLER METAL

Vertical Position Weldbrazements

Aircraft components generally have complicated shapes and joint configurations. Some of these lap joints will be in a vertical position. In order to evaluate filler metal flow for vertical weldbraze joints several 203 mm (8-inch) panels were spot welded and then brazed vertically in a tube retort. These panels had joint gaps ranging from 0.025 mm (0.001-inch) to 0.25 mm (0.010 inch). A representative example of the vertical weldbrazed specimen is shown in Figure 24. A narrow strip of Ti-6A1-4V was spot welded to each side of a base panel. Filler metal 4043 was placed at the upper corner of each face panel edge by spot welding aluminum tabs over the filler metal to hold it in position. Several different quantities of filler metal were used in order to determine the amount of filler metal required to obtain complete brazing without having excess filler metal runoff. An example of optimum filler-metal quantity is shown in Figure 24, Side A. Side B shows that twice the filler-metal quantity used for Side A resulted in excess filler-metal runoff for a uniform joint gap of 0.025 mm (0.001 inch). After evaluating four similar vertical position weldbraze panels with different joint gaps, the following filler-metal quantity formula was devised: 0.05 grams per 0.025 mm (0.001 inch) joint gap per 645 mm^2 (square inch) of lap area. With this formula, successful filler-metal flow occurs across the lap joint and adequate fillets are formed at all edges without excess filler metal runoff.

A second type of vertical position weldbraze test panel was evaluated to determine how well the filler metal would flow upward in spot welded lap joints. Four test panels were spot welded and filler metal 4043 was placed at the bottom edge of each panel with aluminum foil tabs. The panels were then placed on a rack, as shown in Figure 25, and brazed at 920K (1200F). The interface area, joint gap, filler metal quantity and panel angle are shown for each panel. These panels were then inspected for voids at the interface by using untrasonic "C scan" inspection techniques. This inspection showed that excellent filler metal flow occurred in vertical brazements for small and large joint gaps. Panels 1 and 4 had no voids and panels 2 and 3 showed less than 5% voids. These results show that, for inaccessible weldbraze joints, the filler metal can be placed below the portion to be brazed and capillary attraction of the joint will cause upward flow of the filler metal to successfully fill the joint for a distance of at least 50 mm (2 inches) for vertical joints.

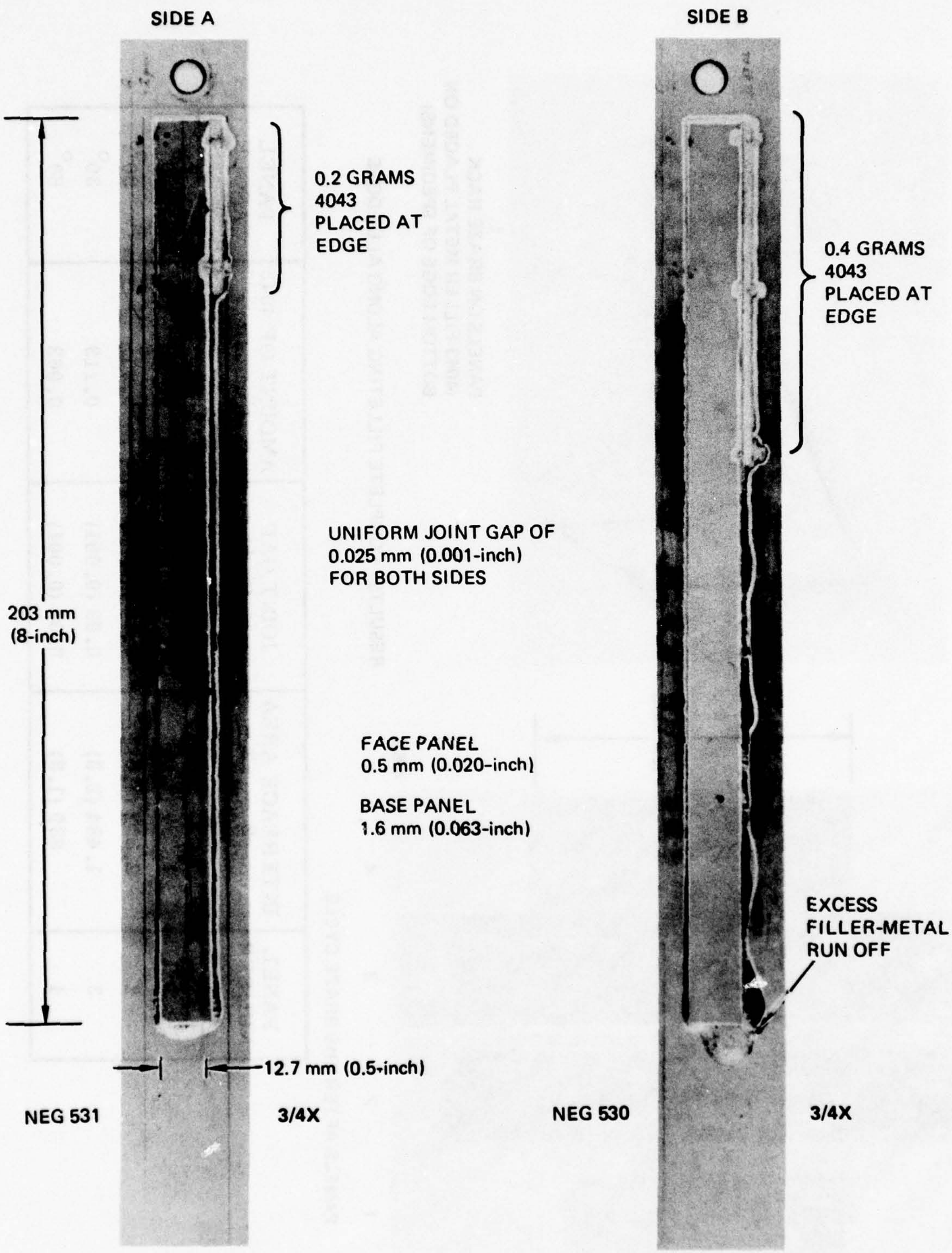
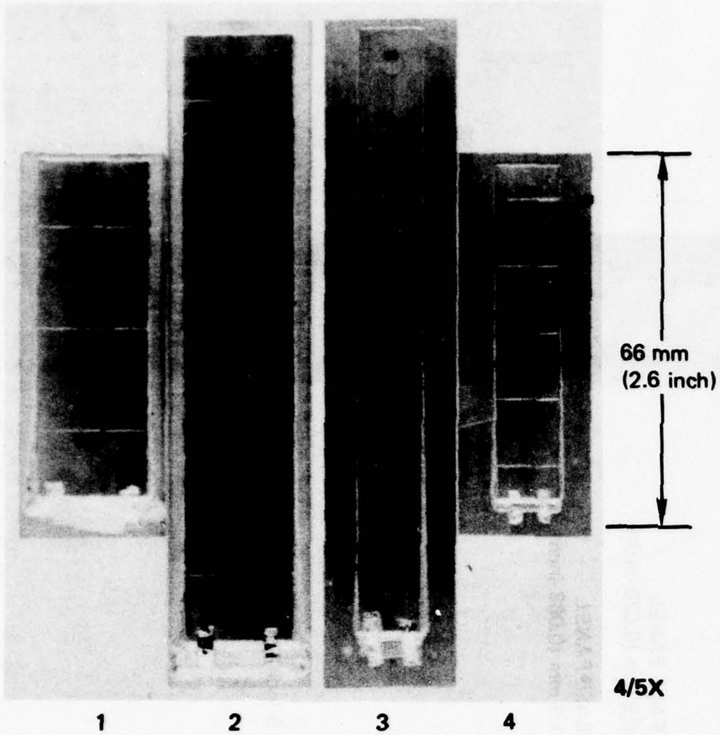
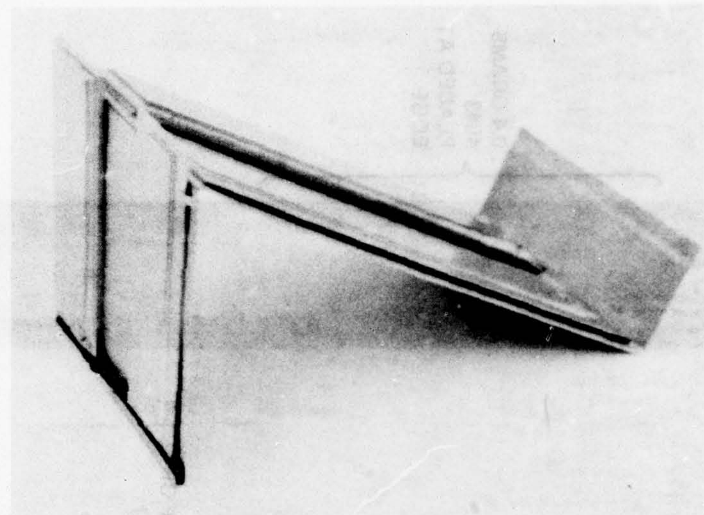


FIGURE 24. VERTICAL POSITION WELDBRAZE PANEL, 0.025 mm (0.001-inch) JOINT GAP



PANELS AFTER THE BRAZE CYCLE



PANELS ON BRAZE RACK
(4043 FILLER METAL PLACED ON BOTTOM EDGE OF SPECIMENS)

RESULTS: COMPLETE FILLETING ALONG ALL EDGES

PANEL NUMBER	INTERFACE AREA mm^2 ($inch^2$)	JOINT GAP mm (inch)	AMOUNT OF 4043 (grams)	PANEL ANGLE
1	1,290 (2.0)	0.15 (0.006)	0.60	80^o
2	2,322 (3.6)	0.13 (0.005)	0.90	30^o
3	1,484 (2.3)	0.03 (0.001)	0.113	30^o
4	839 (1.3)	0.03 (0.001)	0.063	80^o

FIGURE 25. FILLER-METAL FLOW TESTS

The panels in Figure 25 were weldbrazed using the filler metal quantity formula given above. For panels 3 and 4 the use of the formula resulted in excellent fillets and no excess filler metal at the bottom edge of the panels. For panels 1 and 2 (large joint gaps) excellent fillets were obtained but there was a slight excess of filler metal at the bottom edge of the panels. However, the filler metal quantity formula provides a useful method for estimating quantity of filler metal required for producing weldbraze lap joints.

Braze Parameter Summary

An optimum brazing cycle was established in which a partial pressure of argon is used. Screening tests were conducted for five aluminum-base filler metals and alloys 5052, 1100, and AVCO 48 were selected for additional weldbraze property tests. These properties will be compared later in this report to those of weldbraze joints made with filler metals 4043, 3003, 718, 201, and No. 7. Filler metal placement methods were developed for holding the filler metal at the edge of the joint for vertical, inverted, and horizontal weldbrazements. Also, a filler-metal quantity formula was developed which provides a good estimate for determining the amount of filler metal to be used in weldbrazed lap joints.

NON-DESTRUCTIVE INSPECTION TECHNIQUES

Standard radiographic inspection techniques were used throughout this program for non-destructive evaluation of spot welds. This technique was found to be satisfactory for the detection of weld defects. Once the spot welding parameters shown in Table 5 were defined and used for all subsequent spot welding, no weld defects occurred.

Nondestructive inspection techniques for detecting filler-metal voids at the faying surfaces of a weldbrazed joint were also evaluated. Approximately 100 brazed and weldbrazed test specimens were inspected for voids in the joint using ultrasonic C-scan and radiographic methods. Also, all of these test specimens were visually inspected to determine the degree of filler-metal flow and filleting. A visual rating of "good" was given to specimens which exhibited complete filler-metal flow through the lap-joint and formed a small fillet.

The results of this visual inspection compared to the percent voids determined by ultrasonic C-scan and radiographic inspection are shown below:

Ultrasonic and Radiographic Inspection (% Voids)	Complete Filler-Metal Flow (Visual Inspection Rating)	Specimen Code
15	Poor	AA3-3
12	Poor	AA3-1
11	Good	B6-14
10	Poor	BB3-2
10	Poor	BB3-3
7	Good	BB1-9
4	Poor	AA3-2
3	Poor	BB3-1
[(less than 2)]	[(Good)]	[(92 specimens)]

This shows that a reasonably good correlation exists between visual inspection and voids greater than 9% in the joint. Four specimens with a poor visual inspection rating were found to have voids ranging from 10 to 15%. Only one specimen with a "good" visual inspection rating had voids as high as 11%. All other test specimens except AA3-2 and BB3-1 had a "good" visual inspection rating and contained less than 5% voids.

Subsequent tests (discussed in the section "Weldbrazed Properties") have indicated that voids up to at least 15% do not reduce the fatigue life for low-load transfer joints. Since most structural joints are considered to be similar to the low-load transfer joints tested in this program, visual inspection is probably adequate for inspecting non-critical weldbraze joints. It is significant that at least 92 of 100 weldbraze lap-joints revealed less than 2% voids, and that for each of these joints the visual rating was "good." For the "capillary flow" method of weldbrazing there is a very low incidence of gas entrapment or voids occurring at the joint interface as the filler metal flows by capillary action from one edge to the other.

Both the radiographic and ultrasonic inspection methods provided excellent definition of the size and shape of voids at the faying surfaces. Both methods provided the capability for detecting voids as small as 1mm (0.040-inch) diameter. However, each method had some limitations. The effectiveness of ultrasonic inspection for three and four layers has not been determined. In contrast, radiographic inspection of a weldbrazed airframe component conducted at the end of this program was very effective for detecting voids in three and four layer joints. On the other hand, ultrasonic inspection was effective for detecting voids in two layer weldbraze joints having very small gaps e.g., 0.03mm (0.001 inch). It is questionable whether or not radiographic inspection is effective for detecting voids in weldbrazed joints having a gap less than 0.05mm (0.002-inch). However, as indicated in Table 6, the braze gap or sheet separation for typical weldbrazed joints is expected to be greater than 0.05mm (0.002-inch).

The eddy current inspection method was found to be effective for detecting voids larger than 2.5mm (0.1-inch) in diameter. Portable eddy current techniques and portable ultrasonic techniques might be developed so that rapid inspection of critical two-layer joints could be performed on the production line as a supplement to visual inspection.

Non-Destructive Inspection Summary

Based on the non-destructive inspection methods evaluated during this program, it is recommended that visual inspection be considered as the primary, low-cost, method for inspecting non-critical weldbrazed joints. If incomplete filler metal flow is detected (i.e., less than 90% per inch length of any lap edge), or the joint is considered to be critical, then radiographic methods should be used. For flat joints ultrasonic methods are effective for two-layer, weldbrazed joints. With further development eddy current inspection methods could be used to supplement visual inspection of questionable areas.

WELDBRAZE PROPERTIES

Lap-shear strength, stress-rupture strength, cross-tension strength, stress-corrosion resistance and salt fog corrosion properties were determined for Ti-6Al-4V weldbraze joints which have been brazed with filler metals 5052, 1100, and AVCO 48. Both the lap-shear and stress-rupture tests were conducted at 533K (500F), 617K (650F), and 700K (800F); and the lap-shear, cross-tension and stress-corrosion tests were conducted at room temperature. The results of these tests are directly compared with earlier Northrop data for filler metals 3003, 4043, 718, 201, and No. 7, which were obtained with Independent Research and Development (IRAD) funds.

Room temperature fatigue behavior was determined for weldbraze joints which were brazed with filler metal 4043.

The welding and brazing parameters used to weldbraze the test specimens have been described in prior sections of this report. All lap-shear, stress-rupture, stress-corrosion, and salt fog corrosion data was obtained using the following lap-shear specimen configuration: (This configuration was also used for all IRAD data.)

Length:	185mm (7.25 inch)
Width:	25mm (1.0 inch)
Overlap:	19mm (0.75 inch)
Thickness:	1.6mm (0.063 inch)

Lap-Shear Strength

Lap-shear test results for weldbraze joints fabricated with filler metals 5052, 1100, and AVCO 48 are presented in Table 9. At room temperature, the weldbraze joints failed in the base metal rather than at the weldbraze joint interface.

In comparison to a spot welded joint the room temperature strength for each of these weldbraze joints was more than double the strength of the spot weld joint; i.e., 42,200N (9500 lbs.) versus 17,800N (4000 lbs.). At 700K (800F), the weldbraze joints were 40% stronger than the spot weld joints; i.e., 23,000N (5200 lbs.) versus 16,500N (3700 lbs.).

The elevated temperature strength was essentially equal for the 5052 and 1100 weldbrazed joints. However, the elevated temperature strength for the AVCO 48 weldbrazed joint was approximately 15% lower than for the other two filler metals.

TABLE 9. LAP-SHEAR STRENGTH FOR WELDBRAZED Ti-6Al-4V JOINTS

TEST CONDITIONS: 15 TO 30 MINUTES HOLD AT TEMPERATURE BEFORE TEST

HEAD TRAVEL: 1.3 mm (0.05-inch) PER MINUTE

FILLER METAL	TEST TEMPERATURE (K)	(F)	SPECIMEN NUMBER	LAP-SHEAR STRENGTH AVERAGE (N)	(LBS)	AVERAGE (MPa)	(KSI)
SPOTWELD ONLY	295	72	–	17,800	4000		
	700	800	76–440 76–441	16,500	3700 3700		
1100	295	72	–	> 42,200	> 9500*	87.6	> 12.7*
	533	500	76–388 76–389 76–390	30,200	> 6675* > 6800* 6870	62.7	> 8.9* > 9.1* 9.2
	617	650	76–391 76–392 76–393	26,000	5900 5780 5820	53.8	7.9 7.7 7.8
	700	800	76–394 76–395 76–396	22,200	5075 4650 5250	46.2	6.8 6.2 7.0
5052	295	72	–	> 42,200	> 9500*	87.6	> 12.7*
	533	500	76–328 76–329 76–330	30,100	> 6625* > 6950* > 6725*	62.0	> 8.8* > 9.3* > 9.0*
	617	650	76–331 76–332 76–333	27,700	6400 6120 6180	57.2	8.5 8.2 8.2
	700	800	76–334 76–335 76–336	23,500	5125 5250 5450	48.3	6.8 7.0 7.3
AVCO 48	295	72	–	> 42,200	> 9500*	87.6	> 12.7*
	533	500	76–352 76–353 76–354	27,400	6200 6025 6275	53.8	8.0 7.7 7.7
	617	650	76–355 76–356 76–357	24,000	5880 5300 5050	48.3	7.4 7.2 6.5
	700	800	76–358 76–359 76–360	20,100	4680 4450 4420	40.7	6.2 5.7 5.7

*BASE METAL FAILURE AWAY FROM JOINT

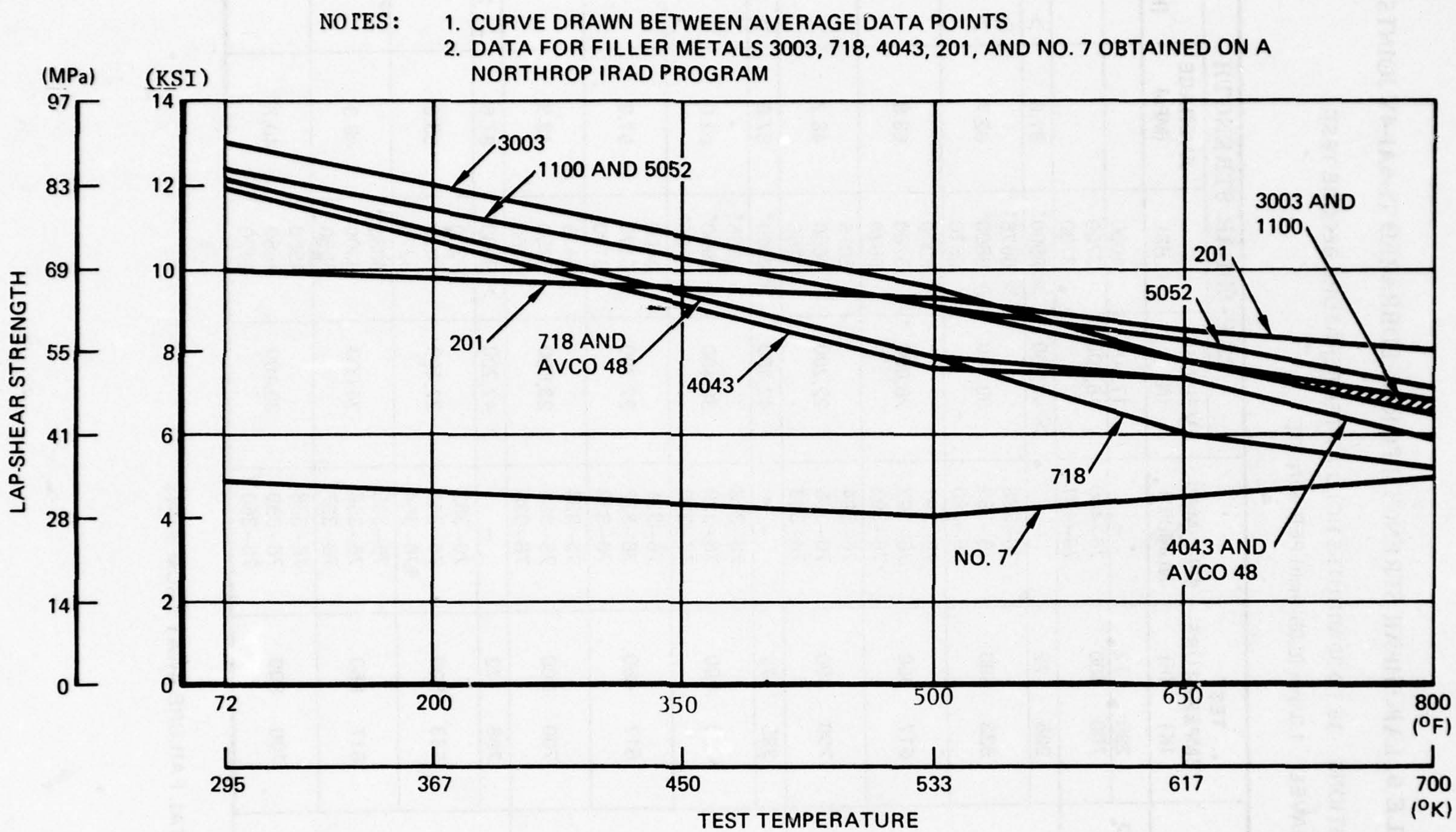


FIGURE 26. LAP-SHEAR STRENGTH FOR WELDBRAZED Ti-6Al-4V JOINTS

The summary plot for the lap-shear strength of eight filler metals is presented in Figure 26. There does not appear to be a major difference in lap-shear strength for most of the filler metals tested. However, based on the limited number of tests conducted, filler metals 201, 5052, 3003, and 1100 have the highest strength at elevated temperatures. Filler metals 4043, 718, and AVCO 48 have lower lap-shear strength; and No. 7 filler metal has a much lower lap-shear strength at test temperatures below 700K (800F).

Cross-Tension Strength

The cross-tension strength for weldbrazed joints as related to eight filler metals is shown in Table 10. The ductility of a filler metal can be related to the ratio of the braze crack load (i.e., load at which the first crack occurs) to the maximum load required to cause cross-tension failure. The lower the ductility of the filler metal, the lower this ratio becomes. On this basis, it can be seen that filler metals 3003, 718, 1100, and 4043 have a high ductility rating followed by 5052, AVCO 48, 201, and No. 7 in order of decreasing ductility.

The resistance to peel is indicated by the load required to cause the first crack in the filler metal and also by the maximum load required to cause cross-tension failure. Based on these two criteria, the filler metals can be ranked in order of decreasing resistance to peel as follows: 1100, 5052, 3003, Avco 48, 718, 4043, 201, and No. 7.

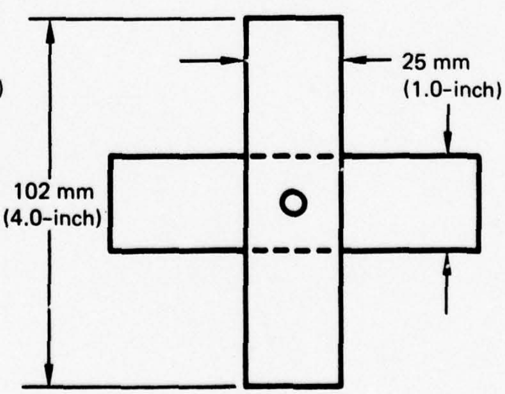
TABLE 10. CROSS-TENSION BEHAVIOR OF WELDBRAZED Ti-6Al-4V

BRAZING FILLER METAL	FIRST CRACK IN BRAZE FILLET AVERAGE (KN)	(LB)	MAXIMUM LOAD AVERAGE (KN)	(LB)	RATIO: BRAZE CRACK LOAD / MAXIMUM LOAD	
3003 (1)		1175		1175	1.00	
	5.38	1210	5.38	1210	1.00	1.0 AVG
		1240		1240	1.00	
718 (1)		1055		1055	1.00	
	4.49	1000	4.56	1005	0.99	0.98 AVG
		965		1015	0.95	
4043 (1)		965		990	0.97	
	4.26	930	4.42	985	0.94	0.96 AVG
		975		1000	0.97	
201 (1)		755		1015	0.74	
	3.51	800	4.53	1060	0.75	0.77 AVG
		810		980	0.82	
NO. 7 (1)		405		935	0.43	
	1.76	365	4.21	945	0.39	0.41 AVG
		415		960	0.43	
1100		1500		1620	0.93	
	7.30	1715	7.48	1715	1.00	0.98 AVG
		1710		1710	1.00	
5052		1360		1480	0.92	
	5.33	1135	6.13	1290	0.88	0.87 AVG
		1100		1365	0.81	
AVCO 48		1100		1230	0.89	
	4.59	882	5.81	1318	0.67	0.79 AVG
		1115		1370	0.81	

(1) DATA OBTAINED ON A NORTHROP IRAD PROGRAM.

SPECIMEN DESIGN:

THICKNESS = 1.6 mm (0.063 inch)



Stress-Rupture Properties

The stress-rupture properties of weldbrazed joints as related to eight filler metals are shown in Figures 27, 28, and 29, and in Tables 11, 12, and 13. These properties were obtained for three temperatures, 533K (500F), 617K (650F) and 700K (800F). Some of the data had been obtained during Northrop IRAD programs as indicated in the data tables.

For comparison purposes, stress-rupture tests were also conducted for spot welded specimens. The specimen configuration was the same for all joints. Doublers were spot welded to the ends of the lap-shear specimens, and 9 mm (0.32-inch) holes were drilled to allow pin loading.

The "spot-weld-only" lap-shear specimens were identical to the weldbraze lap-shear specimens except that filler metal was not present in the lap joint. The lap-shear stress computed for the "spot-weld-only" specimens was based on a lap-shear area equal to that of the weldbraze lap-shear area for direct comparison purposes; i.e., equal dead weight loading for both types of lap-joints for the same stress level.

In general, the stress-rupture behavior of the spot welded joint was equal to or better than most of the weldbrazements tested. Under high stress, long time, elevated temperature conditions, there may be an "embrittlement" effect after the crack has reached the spot weld nugget. Examination of the failed specimens showed that the failures were cohesive, through the filler metal, and final failure occurred by nugget pull-out.

It is difficult to establish trends from these tests since test scatter is high. For example, at 533K (500F), Table 11, the AVCO 48 weldbrazed joint did not fail in 800 hours at a stress level of 41 MPa (6.0 ksi), but did fail in 19 hours and 82 hours at the lower stress level of 38 MPa (5.5 ksi). Also, it is difficult to establish a practical failure stress level for these specimens since "cracking to the nugget" occurred for all specimens which are noted as "run out" tests in the "hours to failure" column of the data tables. Failure could be defined as crack initiation in the weldbrazed joint interface. However, the intent of this weldbraze program was to compare the weldbraze stress-rupture properties of several filler metals, and not to obtain design data for each of these alloys in terms of threshold stress-rupture crack initiation.

NOTES: 1. CURVES REPRESENT MINIMUM STRESS-RUPTURE DATA
2. DATA FOR FILLER METALS 3003, 718, 4043, 201, AND NO. 7 OBTAINED ON A NORTHROP IRAD PROGRAM

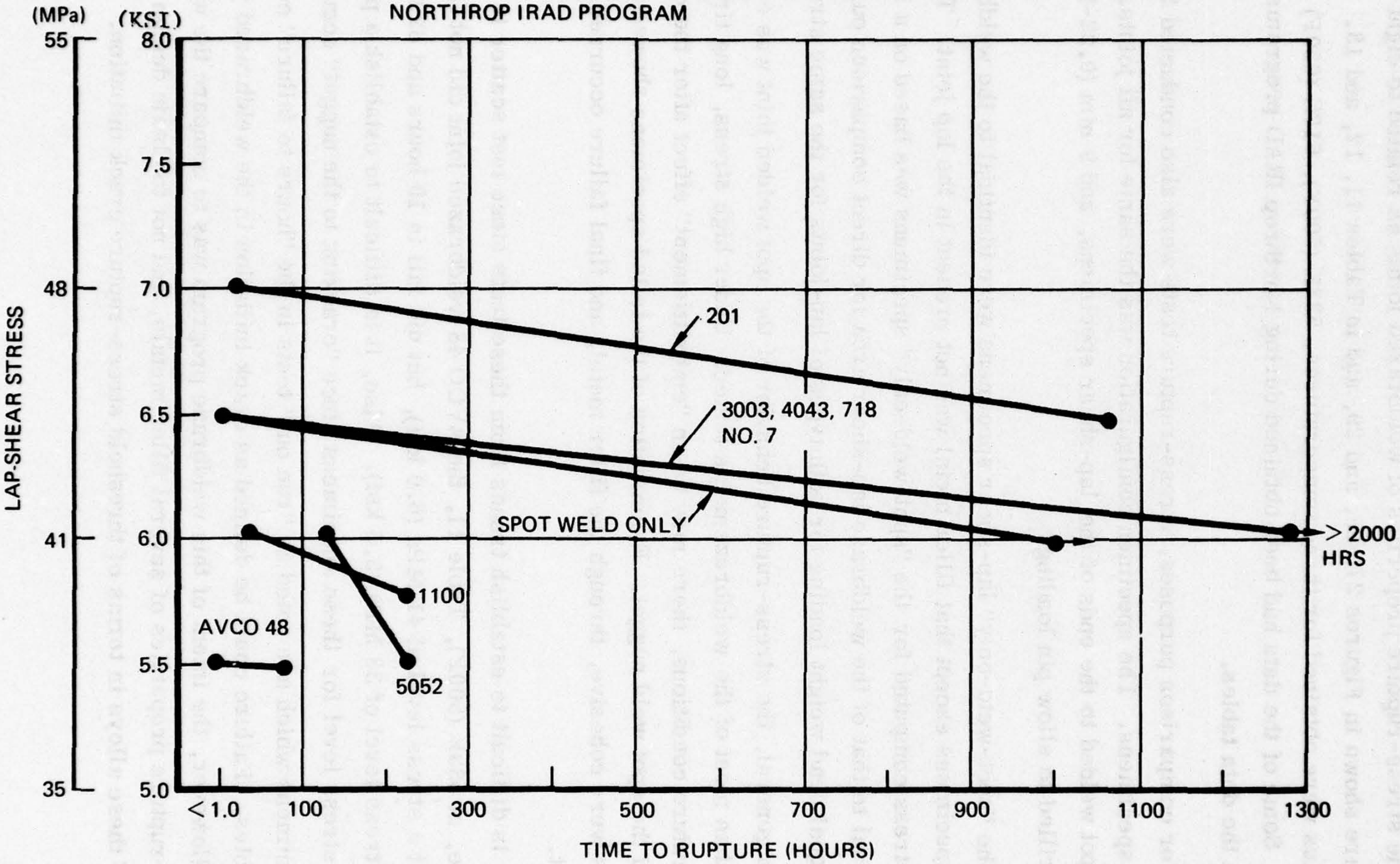


FIGURE 27. STRESS-RUPTURE BEHAVIOR OF WELDBRAZED Ti-6Al-4V AT 533K (500 F)

NOTE: 1. CURVES REPRESENT MINIMUM STRESS-RUPTURE DATA

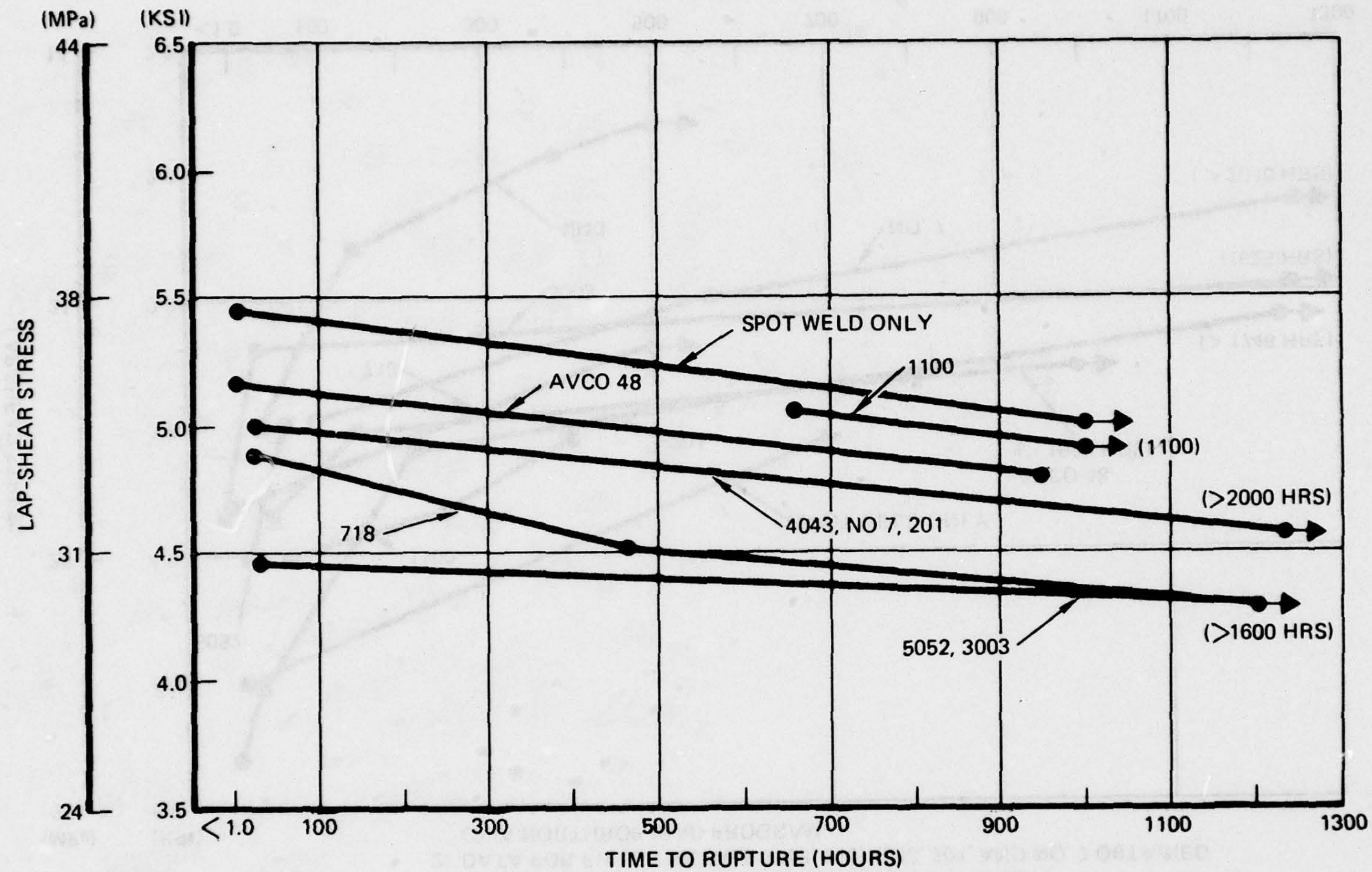


FIGURE 28. STRESS-RUPTURE BEHAVIOR OF WELDBRAZED Ti-6Al-4V AT 617K (650 F)

NOTES: 1. CURVES REPRESENT MINIMUM STRESS-RUPTURE DATA
2. DATA FOR FILLER METALS 3003, 718, 4043, 201, AND NO. 7 OBTAINED ON A NORTHROP IRAD PROGRAM

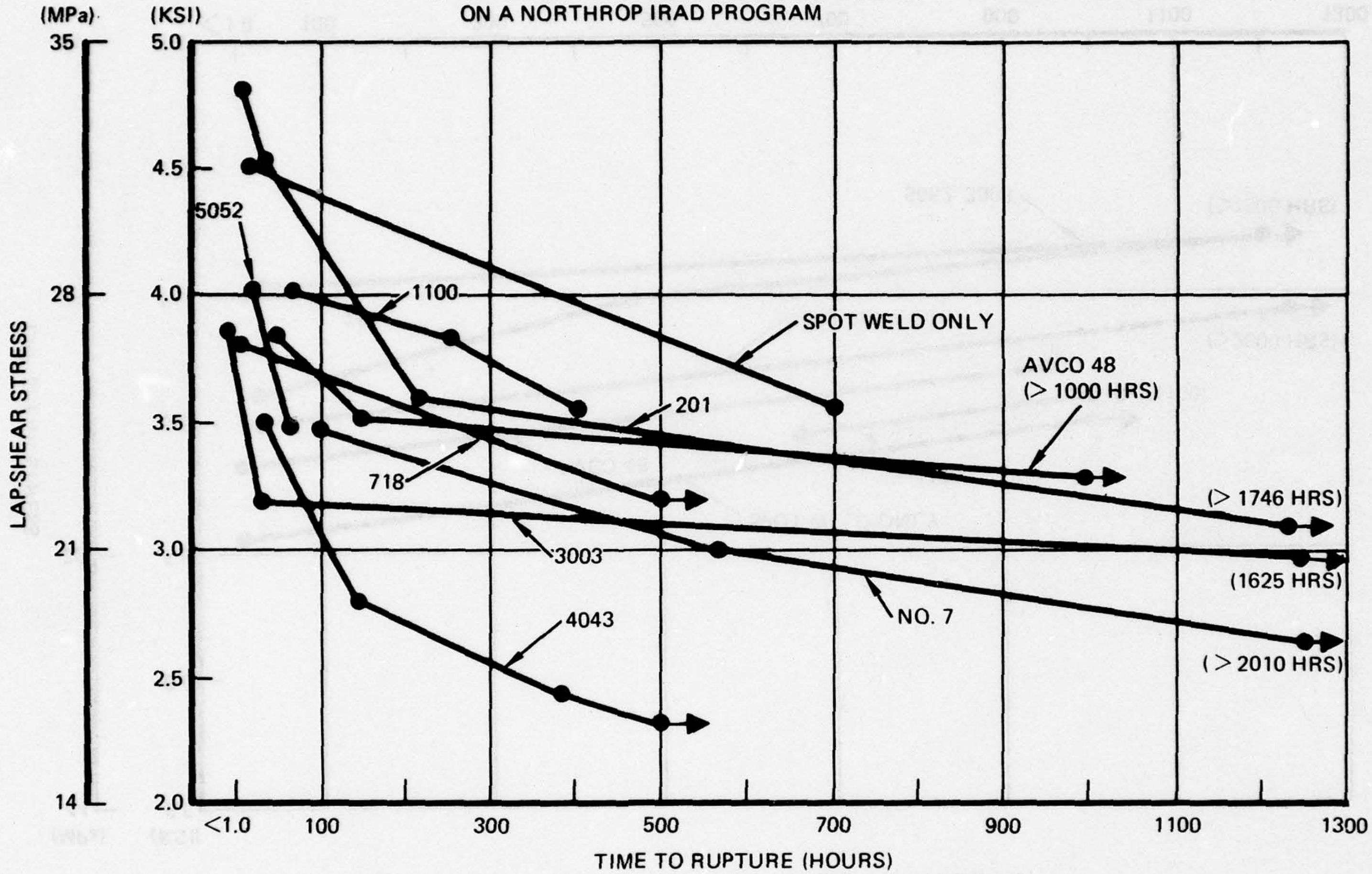


FIGURE 29. STRESS-RUPTURE BEHAVIOR OF WELDBRAZED Ti-6Al-4V AT 700K (800 F)

TABLE 11. STRESS-RUPTURE BEHAVIOR OF WELDBRAZED Ti-6Al-4V AT 533K (500F)

FILLER METAL	SPECIMEN NUMBER	LAP-SHEAR STRESS		HOURS TO FAILURE
		MPa	KSI	
SPOTWELD ONLY (1)	76–431	48	7.0 (2)	FOL (3)
	76–432	45	6.5	FOL
	76–430	41	6.0	> 1008
1100	76–397	45	6.5	60
	76–398	43	6.3	71
	76–399	41	6.0	69
	76–400	40	5.8	187
5052	76–323	45	6.5	71
	76–324	43	6.3	142
	76–325	41	6.0	131
	76–322	38	5.5	232
AVCO 48	76–362	45	6.5	14
	76–363	41	6.0	> 800
	76–361	38	5.5	82
	76–364	38	5.5	19
3003 (1)	76–4	52	7.5	FOL
	76–5	48	7.0	6
	76–10	45	6.5	14
	A–2	41	6.0	> 2001
	A–1	35	5.0	> 2500
4043 (1)	76–26	48	7.0	FOL
	76–27	45	6.5	20
	A–12	41	6.0	> 2360
	A–10	35	5.0	> 2544
718 (1)	76–37	48	7.0	FOL
	76–38	45	6.5	0.1
	A–21	41	6.0	> 2000
	A–19	35	5.0	> 2520
No. 7 (1)	76–43	45	6.5	FOL
	A–29	45	6.5	FOL
	A–30	41	6.0	> 2001
	A–28	35	5.0	> 2520
201 (1)	A–37	55	8.0	14
	A–38	52	7.5	33
	A–57	48	7.0	5
	A–39	45	6.5	1059
	A–58	45	6.5	> 1003

(1) DATA OBTAINED ON A NORTHROP IRAD PROGRAM
(2) SPOTWELD JOINT TEST LOADS HAVE BEEN EQUATED TO THE WELDBRAZE LAP SHEAR AREAS FOR COMPARISON PURPOSES.
(3) FOL = FAILED ON LOADING

TABLE 12. STRESS-RUPTURE BEHAVIOR OF WELDBRAZED Ti-6Al-4V AT 617K (650F)

FILLER METAL	SPECIMEN NUMBER	LAP-SHEAR STRESS MPa	LAP-SHEAR STRESS KSI	HOURS TO FAILURE
SPOTWELD ONLY	76-433	38	5.5 (1)	FOL (2)
	76-437	34	5.0	> 1003
	76-436	31	4.5	> 1005
1100	76-404	34	5.0	643
	76-403	33	4.8	> 1003
	76-401	31	4.5	> 1002
	76-402	29	4.3	> 1002
5052	76-320	31	4.5	20
	76-318	29	4.3	> 1598
	76-321	28	4.0	> 1598
AVCO 48	76-368	36	5.2	0.6
	76-367	34	5.0	> 1002
	76-366	33	4.8	946
	76-365	31	4.5	> 1003
3003	76-6	38	5.5	0.5
	76-7	34	5.0	1.8
	76-8	31	4.5	38
	76-9	28	4.0	> 2000
4043	76-28	38	5.5	0.4
	76-29	34	5.0	23
	76-30	31	4.5	> 2000
718	76-39	38	5.5	FOL
	76-40	34	5.0	0.3
	76-41	31	4.5	461
	76-42	28	4.0	> 2000
NO. 7	76-44	34	5.0	FOL
	76-48	32	4.7	743
	76-45	31	4.5	> 2000
201	76-16	41	6.0	8.8
	76-14	38	5.5	335
	76-18	36	5.3	694
	76-15	34	5.0	443
	76-17	31	4.5	> 2000

(1) SPOTWELD JOINT TEST LOADS HAVE BEEN EQUATED TO THE WELDBRAZE LAP SHEAR AREAS FOR COMPARISON PURPOSES.

(2) FOL = FAILED ON LOADING

TABLE 13. STRESS-RUPTURE BEHAVIOR OF WELDBRAZED Ti-6Al-4V AT 700K (800F)

FILLER METAL	SPECIMEN NUMBER	LAP-SHEAR STRESS MPa	LAP-SHEAR STRESS KSI	HOURS TO FAILURE
SPOTWELD ONLY (1)	76-438	31	4.5 (2)	5
	76-439	24	3.5 (2)	713
1100	76-406	28	4.0	80
	76-405	26	3.8	249
	76-407	24	3.5	602
	76-408	24	3.5	411
5052	76-317	28	4.0	19
	76-316	26	3.8	113
	76-326	24	3.5	65
	76-327	24	3.5	35
AVCO 48	76-370	28	4.0	30
	76-369	26	3.8	44
	76-371	24	3.5	159
	76-372	22	3.2	> 1000
3003 (1)		35	5.0	0.1
		26	3.8	2.3
		22	3.2	38
		20	2.9	1625
4043 (1)		27	3.9	0.2
	76-31	24	3.5	49
		19	2.8	152
		16	2.4	381
		15	2.3	> 500
718 (1)		28	4.0	0.1
		25	3.7	11.3
		22	3.2	> 500
		20	2.9	> 500
NO. 7 (1)	76-46	24	3.5	100
		21	3.0	560
		18	2.6	> 2010
		14	2.2	> 888
201 (1)		33	4.8	21
		31	4.5	39
		28	4.0	336
		24	3.5	215
	76-19	21	3.0	> 1746

(1) DATA OBTAINED ON A NORTHROP IRAD PROGRAM

(2) SPOTWELD JOINT TEST LOADS HAVE BEEN EQUATED TO THE WELDBRAZE LAP SHEAR AREAS FOR COMPARISON PURPOSES.

Based on only three or four stress-rupture tests for each filler metal at a specific test temperature the following comparative ratings for the filler metals are presented below:

Temperatures	Stress-Rupture Rating		
	Highest	Average	Lowest
533K (500F)	201	4043 3003 718 No. 7	1100 5052 AVCO 48
617K (650F)	1100	AVCO 48 4043 No. 7 201	718 5052 3003
700K (800F)	201 1100	AVCO 48 718 5052 3003 No. 7	4043

Corrosion Resistance

The corrosion resistance of weldbrazed joints was evaluated by two different methods: stress-corrosion and exposure to salt fog. After each type of corrosion exposure, the lap-shear specimens were tested at room temperature to determine the residual strength and to estimate the extent of corrosion that occurred at the lap-joint interface during the exposure.

Stress-Corrosion Exposure: For the stress-corrosion exposure the weldbrazed lap-shear specimens were deadweight loaded in creep frames to 50%, 60%, and 70% of the room temperature joint strength previously determined for each filler metal. The weldbraze joint area was surrounded by a plastic container so that the joint was submerged in a 3.5% NaCl solution at room temperature for 1000 hours. The solution was replaced with a fresh solution once a week during the six-week exposure.

The lap-shear strength after exposure is presented in Table 14 and Table 15. Filler metals 1100, and 4043, were unaffected by these stress-corrosion conditions as 100% of their original strength was retained. Filler-metals 3003, 718 and 5052 lost less than 25% of their original weldbraze strength, with less than 15% corrosion at the joint for filler metals 3003 and 718; and less than 50% corrosion at the joint for

TABLE 14. STRESS-CORROSION BEHAVIOR OF WELDBRAZED LAP-SHEAR JOINTS FOR FILLER METALS 5052, 1100, AND AVCO 48

EXPOSURE CONDITIONS: 3.5% NaCl SOLUTION AT ROOM TEMPERATURE FOR 1000 HOURS

FILLER METAL	EXPOSURE STRESS LEVEL (1)		SPECIMEN CODE	PERCENT OF JOINT CORRODED	RESIDUAL STRENGTH		PERCENT OF ORIGINAL STRENGTH (2)
	MPa	KSI			MPa	KSI	
5052	41.4	6.0	76-337	10	72.4	10.5	88
			76-338	10	68.3	9.9	83
			76-339	20	65.5	9.5	79
	49.6	7.2	76-340	20	68.9	10.0	83
			76-341	10	71.0	10.3	86
			76-342	20	67.6	9.8	82
	57.9	8.4	76-343	50	66.2	9.6	80
			76-344	50	70.3	10.2	85
			76-345	50	62.7	9.1	76
1100	41.4	6.0	76-409	0	> 87.6	> 12.7 (3)	100
			76-410	0	88.9	12.9	100
			76-411	0	> 86.9	> 12.6 (3)	100
	49.6	7.2	76-412	0	86.2	12.5	100
			76-413	0	> 87.6	> 12.7 (3)	100
			76-414	0	> 76.5	> 11.1 (3)	N/A (3)
	57.9	8.4	76-415	0	82.0	11.9	99
			76-416	5	75.1	10.9	91
			76-417	0	> 76.5	> 11.1 (3)	N/A (3)
AVCO 48	41.4	6.0	76-373	40	56.5	8.2	68
			76-374	30	62.7	9.1	76
			76-375	30	69.6	10.1	84
	49.6	7.2	76-376	100	(FAILED IN 829 HOURS)		
			76-377	40	62.0	9.0	75
			76-378	100	(FAILED IN 883 HOURS)		
	57.9	8.4	76-379	100	(FAILED IN 494 HOURS)		
			76-380	100	(FAILED IN 495 HOURS)		

(1) STRESSED AT 50, 60, AND 70% OF THE ROOM TEMPERATURE LAP-SHEAR STRENGTH OF 82.7 MPa (12.0 KSI).

(2) ORIGINAL STRENGTH = 82.7 MPa (12.0 KSI). STRENGTH OF SPOT WELD = 47% OF ORIGINAL STRENGTH.

(3) FAILED IN BASE METAL AWAY FROM LAP JOINT.

TABLE 15. STRESS-CORROSION BEHAVIOR OF WELDBRAZED LAP-SHEAR JOINTS FOR FIVE FILLER METALS

DATA OBTAINED ON A NORTHROP IRAD PROGRAM

EXPOSURE CONDITIONS: 3.5% NaCl SOLUTION AT ROOM TEMPERATURE FOR 1175 HOURS

FILLER METAL	EXPOSURE STRESS LEVEL (1)		PERCENT OF JOINT AREA CORRODED	RESIDUAL STRENGTH		PERCENT OF ORIGINAL STRENGTH
	MPa	KSI		MPa	KSI	
3003	43.4	6.3	0	68.9	10.0	78
	51.7	7.5	5	89.6	13.0	100
	60.7	8.8	10	80.0	11.6	90
4043	32.4	4.7	0	69.6	10.1	100
	39.3	5.7	0	72.4	10.5	100
	45.5	6.6	0	75.8	11.0	100
718	41.4	6.0	10	75.1	10.9	89
	50.3	7.3	15	71.7	10.4	85
	58.6	8.5		FAILED DURING EXPOSURE		
201	34.5	5.0	40	43.4	6.3	63
	41.4	6.0	50	46.2	6.7	68
	48.3	7.0	55	48.3	7.0	71
NO. 7	15.6	2.3	100	34.5	5.0	(2)
	19.3	2.8	100	33.8	4.9	(2)
	22.8	3.3	100	34.5	5.0	(2)

(1) STRESSED AT 50, 60, AND 70% OF THE ROOM TEMPERATURE LAP-SHEAR STRENGTH:

FILLER METAL:	MPa	(KSI)
3003	88.2	(12.8)
4043	66.2	(9.6)
718	84.1	(12.2)
201	68.3	(9.9)
NO. 7	33.1	(4.8)

(2) FILLER METAL COMPLETELY CORRODED AWAY, THEREFORE RESIDUAL STRENGTH REFLECTS STRENGTH OF THE SPOT WELD WHICH REMAINED UNAFFECTED BY THE STRESS-CORROSION ENVIRONMENT.

filler metal 5052. The remaining three filler metals 201, No. 7, and AVCO 48 showed much more corrosion at the joint and a high loss in lap-shear strength.

The effect of increased exposure stress levels on residual strength was minimal. However, the effect of increased stress levels did have a minor influence on the extent of corrosion at the joint for filler-metals 5052, 3003, 718, and 201 indicating a small stress-corrosion effect.

Salt Fog Exposure: The second method used to evaluate the corrosion resistance of weldbrazed joints was to expose the lap-shear specimens to a salt fog environment for 30 and 60 days. This work was performed on a Northrop IRAD Program. Lap-shear tests were conducted after the two exposures to determine the residual strength and percent corrosion at the joint as was done for the stress-corrosion specimens. Two weldbrazed specimens each for filler metals 4043, 3003, and 201 were anodized, using the standard sulphuric acid anodize, prior to the 30- and 60-day exposure. All specimens were placed in a salt fog chamber at 308K (95F) which utilized a 5.0% NaCl aqueous solution. Details of this exposure environment are described in the test standard, ASTM-B117-73.

The results of these tests are shown in Table 16 and Figure 30. For the 30-day exposure, filler metals 4043 and 3003 showed no loss in weldbraze strength. Filler metals 1100 and 5052 showed only a 10% loss in strength. Filler metals 2319, AVCO 48 Amdry 389, and 201, lost essentially all of the strength obtained from the filler metal. The 34 MPa (5 ksi) strength remaining for these specimens represents spot weld strength only. No benefit resulted for the anodized surfaces for the 30-day exposure tests.

For the 60-day exposure, filler metals 1100, 5052, and 3003 showed only a 25% loss in strength. Filler metal 4043 lost approximately 45% of its original weldbrazed strength. For this exposure time the anodized surface for 4043 and 3003 provided a significant improvement in salt fog corrosion resistance when compared to similar joints which were not anodized. The anodized 3003 joint retained 100% of its original weldbraze strength and the anodized 4043 joint retained about 90% of its original strength.

TABLE 16. SALT FOG CORROSION BEHAVIOR OF WELDBRAZED Ti-6Al-4V

EXPOSURE CONDITIONS: 5.0% NaCl AQUEOUS SOLUTION PER ASTM-B117-73 AT 308K (95 F)

EXPOSURE TIME (DAYS)	FILLER METAL	SPECIMEN NUMBER	PERCENT OF JOINT CORRODED	RESIDUAL STRENGTH MPa	RESIDUAL STRENGTH KSI (1)	PERCENT OF ORIGINAL STRENGTH (2)
30	1100	76-418	5	80	11.6	97
		76-419	10	75	10.9	91
		76-420	5	74	10.8	90
	5052	76-346	5	74	10.8	90
		76-347	5	74	10.8	90
		76-348	5	74	10.8	90
	AVCO 48	76-382	70	41	6.0	50
		76-383	60	40	5.8	48
		76-385	75	39	5.6	47
	2319	76-424	70	40	5.8	58
		76-425	75	39	5.7	57
		76-426	75	37	5.4	54
	4043	76-260	30	81	11.7	98
		76-263 (3)	8	83	12.0	100
	3003	76-272	N/A	>83	>12.0 (4)	100
		76-275 (3)	N/A	>83	>12.0 (4)	100
	201	76-284	90	39	5.6	56
		76-287 (3)	85	40	5.8	58
	AMDRY 389	389-4	65		5.6	49
60	1100	76-421	25	77	11.1	93
		76-422	35	59	8.6	72
		76-423	40	61	8.8	73
	5052	76-349	15	73	10.6	88
		76-350	20	61	8.9	74
		76-351	15	63	9.2	77
	AVCO 48	76-384	100	37	5.3	44
		76-386	100	34	4.9	41
		76-387	100	34	4.9	41
	2319	76-427	100	32	4.6	46
		76-428	100	34	4.9	49
		76-429	100	39	5.7	57
	4043	76-261	60	47	6.8	57
		76-264 (3)	20	73	10.6	88
	3003	76-273	15	64	9.3	78
		76-276 (3)	5	>77	>11.2 (4)	>93
	201	76-285	100	38	5.5	55
		76-288 (3)	100	46	6.6	66
	AMDRY 389	76-299	80	38	5.5	48

(1) STRENGTH OF SPOT WELD WITHOUT FILLER METAL CORRESPONDS TO 38 MPa (5.5 KSI)
(2) ORIGINAL WELDBRAZE STRENGTH: 82.7 MPa (12 KSI) FOR 1100, 5052, 4043, 3003, AND AVCO 48; 80 MPa (11.5 KSI) FOR AMDRY 389, AND 69 MPa (10 KSI) FOR 2319, AND 201
(3) LAP JOINT AREA WAS ANODIZED PRIOR TO EXPOSURE
(4) FAILED IN BASE METAL AWAY FROM LAP JOINT

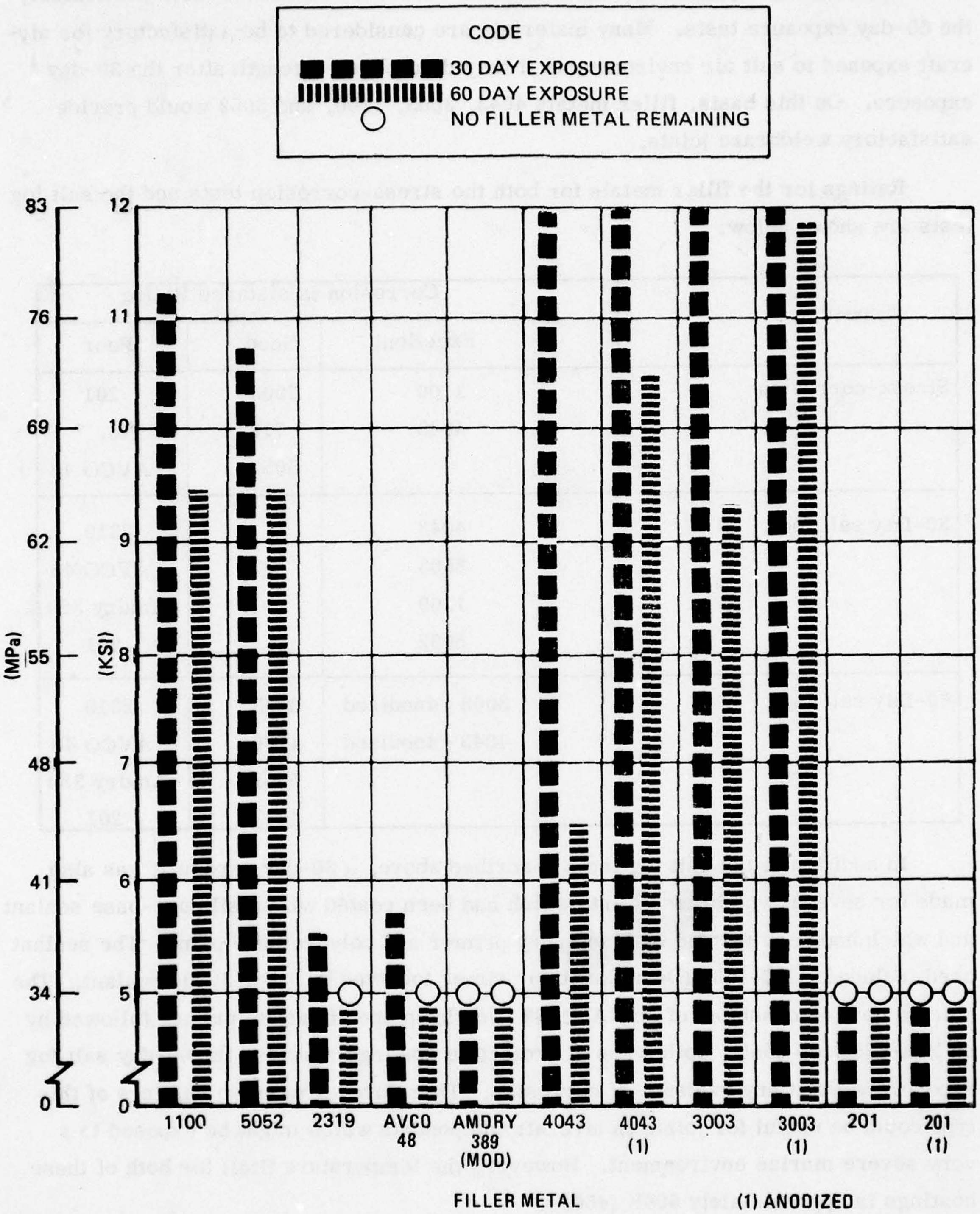


FIGURE 30. LAP-SHEAR STRENGTH OF WELDBRAZED Ti-6Al-4V AFTER SALT FOG EXPOSURE

The salt fog exposure is considered to be a severe corrosion test, particularly the 60-day exposure tests. Many materials are considered to be satisfactory for aircraft exposed to salt air environments if they do not lose strength after the 30-day exposure. On this basis, filler metals 4043, 3003, 1100, and 5052 would provide satisfactory weldbraze joints.

Ratings for the filler metals for both the stress-corrosion tests and the salt fog tests are shown below.

Exposure	Corrosion Resistance Rating		
	Excellent	Good	Poor
Stress-corrosion	1100	3003	201
	4043	718	No. 7
		5052	AVCO 48
30-Day salt fog	4043		2319
	3003		AVCO 48
	1100		Amdry 389
	5052		201
60-Day salt fog	3003 - anodized	3003	2319
	4043 - anodized	1100	AVCO 48
		5052	Amdry 389
		4043	201

In addition to the salt fog tests described above, a 60-day exposure was also made for several weldbrazed joints which had been coated with a silicone-base sealant and which had been painted with an epoxy primer and polyurethane paint. The sealant used included a DC-1200 (Dow-Corning) primer followed by a DC-90006 sealant. The painted coating consisted of an NAI-1269 (Northrop specification) primer followed by an NAI-1290 top coat. Both types of protective coatings survived the 60-day salt fog exposure without any evidence of corrosion. Therefore, protective coatings of this type could be useful for joints in aircraft components which might be exposed to a very severe marine environment. However, the temperature limit for both of these coatings is approximately 506K (450F).

Fatigue Behavior

Fatigue behavior for Ti-6Al-4V weldbraze joints was determined using two types of specimens which represent the loading condition extremes for aircraft joints. These two types of fatigue specimens are the low load transfer joint design and the high load transfer joint design, as shown in Figure 31. In most aircraft joints, the actual loads create stress patterns which combine the conditions represented by the low load and the high load transfer fatigue specimens. Therefore, these tests were conducted to establish fatigue behavior of weldbraze Ti-6Al-4V joints for the two extremes of load transfer conditions. A sheet thickness of 1.6 mm (0.063 inch) was used for these tests.

Fatigue behavior was determined for weldbrazed joints and compared to similar data for mechanically fastened joints, spot welded joints, and brazed joints. Brazing filler metal 4043 was used for all of the fatigue specimens. Several weldbraze joint variables were evaluated in order to develop an optimum weldbraze joint design for high load transfer fatigue applications. Joint variables included single row versus double row spot welds, 19mm (0.75 inch) overlap versus 38mm (1.50 inch) overlap, small weld nugget diameter versus Class A weld nugget diameter, one spot weld versus three spot welds across a 51mm (2.0 inch) width test section, small filler-metal fillet versus a large filler-metal fillet, and either a 30° inside lap edge bevel or a 30° outside lap edge bevel versus the 90° lap edge, to show the effect of very small and very large fillets.

After evaluating several weldbraze joint designs for high load transfer, a single lap joint specimen was selected (Figure 31) and S/N curves were established for both the high load transfer and the low load transfer joint design.

Low Load Transfer Joints: The fatigue data for the low load transfer joint is presented in Table 17. The same test conditions were used for all tests, except as noted in the table. There was no significant difference in fatigue life for the four types of joints (bolts, spot welds, brazements and weldbrazements) represented. Also, the spot weld spacing or number of spot welds along the length of the specimen had no effect on the fatigue life of the weldbrazed joints.

The scatter band for the weldbrazed specimens was between 79,000 cycles and 441,000 cycles to failure. This scatter band includes many more tests than were conducted for the other types of joints and includes data for two different heats of titanium.

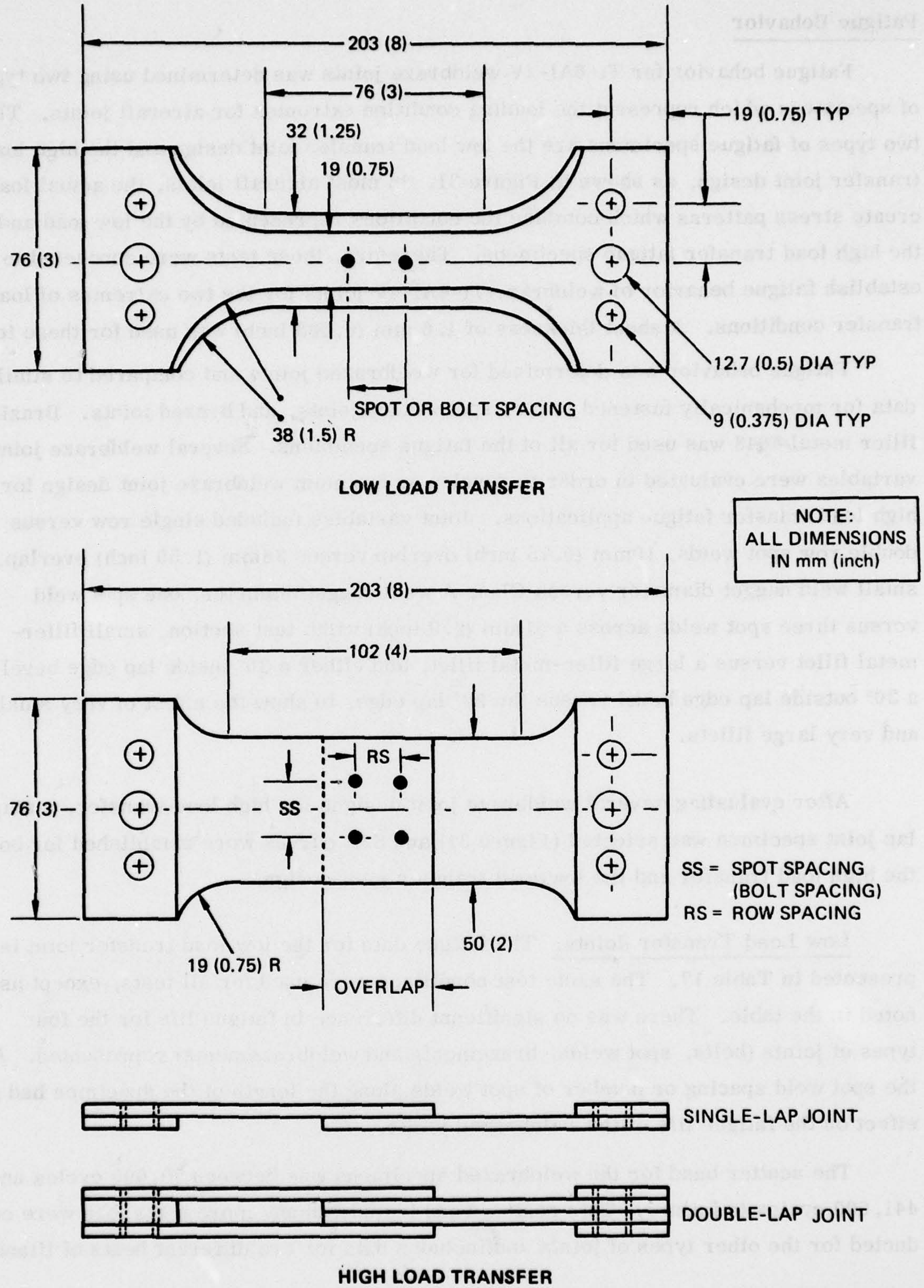


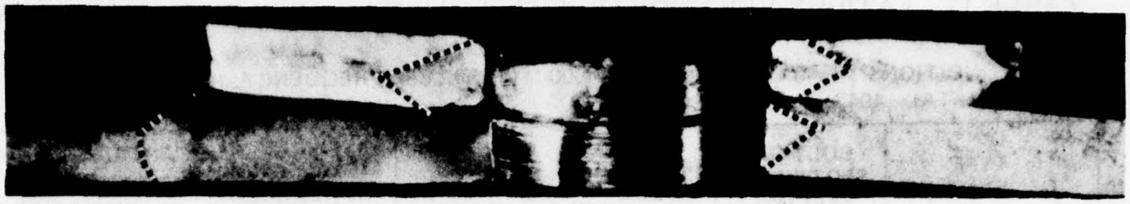
FIGURE 31. FATIGUE SPECIMENS FOR LOW LOAD AND HIGH LOAD TRANSFER

TABLE 17. FATIGUE BEHAVIOR OF LOW LOAD TRANSFER Ti-6Al-4V JOINTS

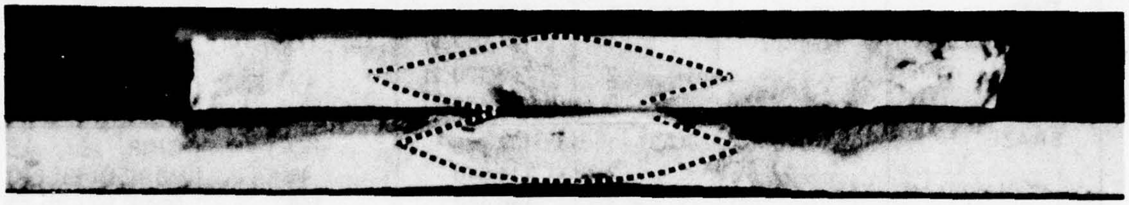
TEST CONDITIONS: R = 0.1; MAX. LOAD, 27,800 N (6,250 LBS); FREQUENCY, 10 Hz
FILLER METAL: 4043

TYPE JOINT	BOLT OR SPOT WELD SPACING	SPECIMEN CODE	CYCLES TO FAILURE	FILLER METAL VOIDS IN REDUCED SECTION (5)	LOCATION OF FATIGUE INITIATION
TWO BOLTS	25 mm	AA1 – 1	>125,690		GRIP AREA
6 mm	(1-inch)	– 2	159,240(1)		BOLT HOLE
(0.25-inch) DIA		– 3	133,960(1)		BOLT HOLE
TWO	25 mm	AA2 – 0	205,110		NUGGET EDGE
SPOT WELDS	(1-inch)	– 1	191,510(1)		NUGGET EDGE
		– 2	50,790(2)		NUGGET EDGE
		– 3	>48,460(2)		GRIP AREA
BRAZE		AA3 – 1	>148,270	12%	GRIP
		– 2	114,540	4%	PORE IN FILLET
		– 3	166,440	15%	PORE IN FILLET
BRAZE 0.5 mm		BB3 – 1	160,770	3%	PORE IN FILLET (4)
(0.020-inch)		– 2	111,470	10%	PORE IN FILLET
EDGE GAP		– 3	326,870	10%	JOINT EDGE
BRAZE		AA3 – 4	143,270	NONE	PORE IN FILLET
(6)		– 5	119,350	NONE	PORE IN FILLET
		– 6	117,440	NONE	PORE IN FILLET (4)
WELDBRAZE	25 mm	AA4 – 1	341,780	NONE	PORE IN FILLET
TWO SPOT	(1-inch)	– 2	247,950	NONE	JOINT EDGE
WELDS (3)		– 3	315,170	NONE	JOINT EDGE
WELDBRAZE	25 mm	BB1 – 1	348,820	NONE	JOINT EDGE (4)
TWO SPOT	(1-inch)	– 2	280,540	NONE	JOINT EDGE (4)
WELDS		– 3	258,750	NONE	PORE IN FILLET
WELDBRAZE	13 mm	BB2 – 1	364,550	<1%	JOINT EDGE
THREE SPOT	(0.5-inch)	– 2	371,240	3%	JOINT EDGE (4)
WELDS		– 3	441,210	1%	JOINT EDGE (4)
WELDBRAZE	19 mm	CC1 – 1	93,280	NOT	JOINT EDGE
SEVEN SPOT	(0.75-inch)	– 2	79,020	INSPECTED	PORE IN FILLET
WELDS (6)		– 3	123,910		JOINT EDGE
WELDBRAZE	25 mm	CC2 – 1	89,750	NOT	JOINT EDGE
FOUR SPOT	(1.0-inch)	– 2	129,090	INSPECTED	PORE IN FILLET
WELDS (6)		– 3	121,490		PORE IN FILLET (4)
WELDBRAZE	38 mm	CC3 – 1	153,540	NOT	JOINT EDGE
THREE SPOT	(1.5-inch)	– 2	94,130	INSPECTED	PORE IN FILLET
WELDS (6)		– 3	82,090		PORE IN FILLET (4)

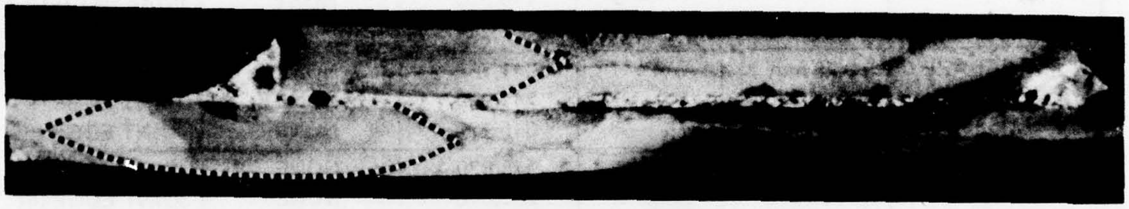
(1) CRACK INITIATION OBSERVED TO BE WITHIN 3% OF NUMBER OF CYCLES TO FAILURE
(2) MAX. LOAD, 37,800 (8,500 LBS)
(3) SMALL NUGGET DIAMETER: 5 mm (0.22-inch)
(4) AT SMALL PANEL RADIUS
(5) FILLER-METAL VOIDS WERE DETECTED BY RADIOGRAPHY
(6) FATIGUE SPECIMENS WERE MACHINED FROM A DIFFERENT HEAT OF Ti-6Al-4V THAN OTHER TEST SPECIMENS IN THIS TABLE



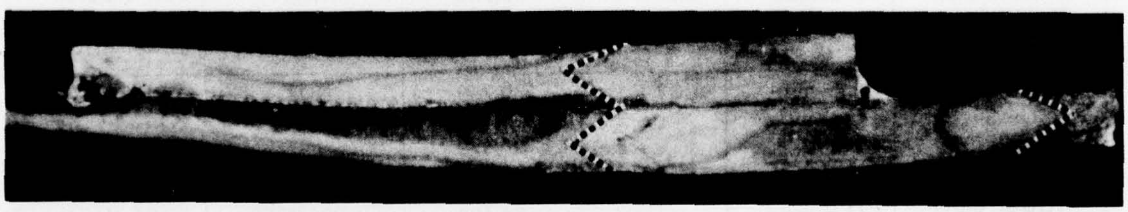
BOLTED



SPOT WELDED



BRAZED



WELDBRAZED 5X

FIGURE 32. TYPICAL FATIGUE FRACTURES FOR LOW-LOAD TRANSFER JOINTS, Ti-6Al-4V

All failures for the weldbrazed joints occurred at the edge of the joint rather than at the spot weld nugget. Therefore, the small nugget diameter used for the specimen AA4 series had no effect on fatigue life. All failures for the brazed joint also occurred at the edge of the joint. Failures for the spot welded joints initiated at the edge of the nugget and progressed through the sheet thickness as expected. Failures for the bolted specimens initiated at the edge of the bolt hole. Typical fatigue fractures for these specimens are shown in Figure 32.

Brazed and weldbrazed joints were inspected by radiography prior to fatigue test to determine quality of the braze. Of the nine weldbraze specimens examined, only three showed any evidence of voids, i.e., less than 3% voids. Of the nine brazed specimens, six showed voids covering up to 15% of the reduced section area. Typical examples of the random shapes of voids and their relation to the fatigue initiation site are shown in Figures 33 and 34. In each case the failure initiation site was not related to the presence of the voids. In fact two of the brazed specimens, BB3-3 and AA3-3, which contained 10% and 15% voids, had the longest fatigue life for the group of six specimens. Therefore, based on these limited data, the presence of filler metal voids up to 15% in a low load transfer joint does not decrease the fatigue life of the joint.

Radiographic inspection made after the tests indicated that cracks did not propagate from the voids into the brazed area during fatigue loading.

High Load Transfer Joints (Double-Lap Joints): The fatigue data for the high load transfer joint is presented in Table 18 for double-lap joints. Unfortunately this specimen configuration provided too strong a joint for comparing the fatigue life of weldbrazed joints to that of the bolted joint for large overlaps. Failure was transferred to the grip area for both the bolted specimen and the weldbrazed specimen for the 50mm (2.0 inch) overlap. However, for the small overlap of 19mm (0.75 inch) which would be typical for spot welded or weldbraze joints, a good comparison can be made for the spot welded, brazed, and weldbrazed joint. The brazed and weldbrazed joints had a fatigue life ranging from 153,000 cycles to 429,000 cycles which was much more than a factor of 10 greater than that for spot welded joints.

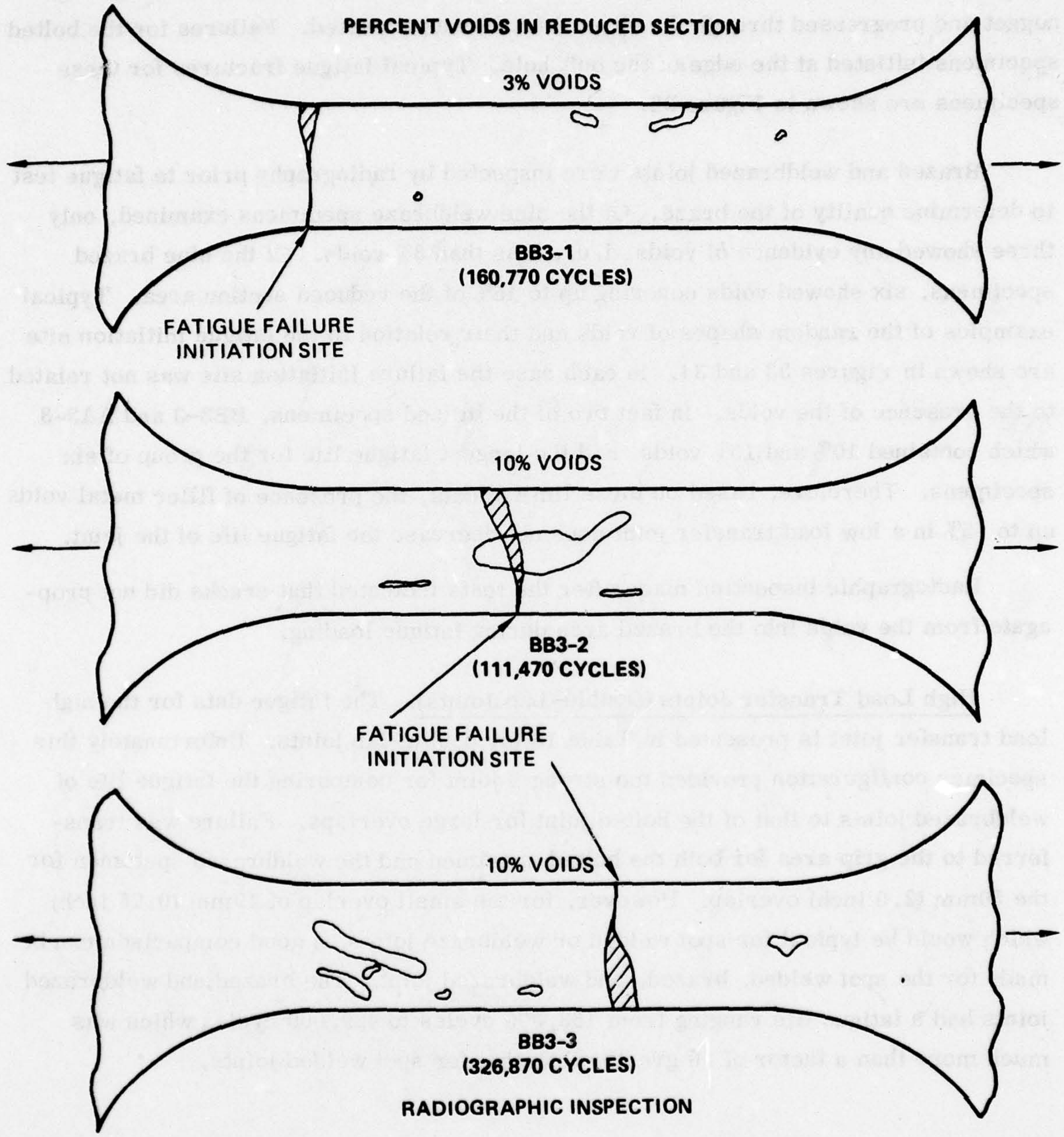


FIGURE 33. FILLER-METAL VOIDS AND FAILURE LOCATION FOR LOW LOAD TRANSFER Ti-6Al-4V BRAZE JOINTS

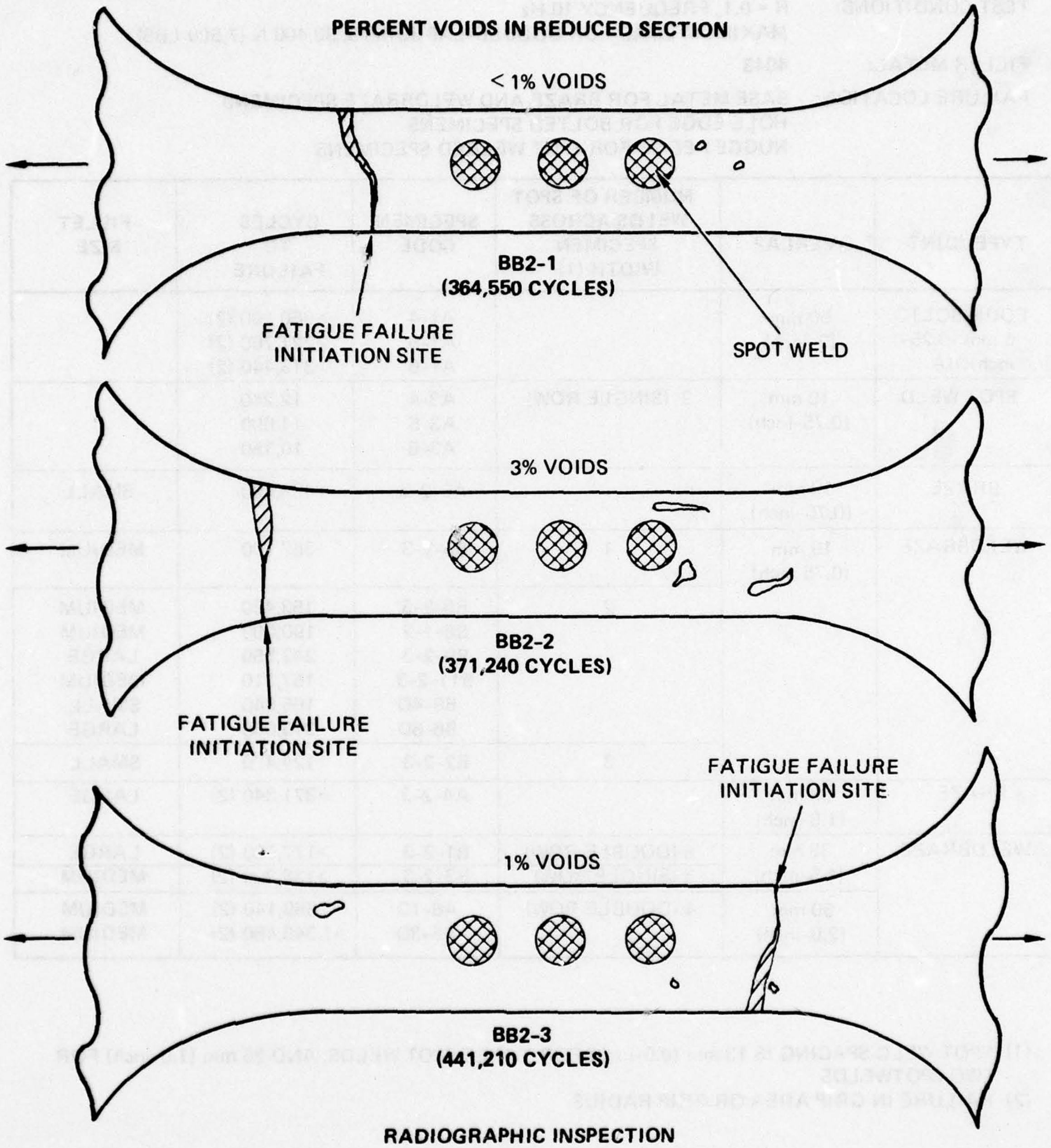


FIGURE 34. FILLER-METAL VOIDS AND FAILURE LOCATION FOR LOW LOAD TRANSFER Ti-6Al-4V WELDBRAZE JOINTS

TABLE 18. FATIGUE BEHAVIOR OF HIGH LOAD TRANSFER Ti-6A1-4V JOINTS – DOUBLE-LAP JOINTS

SPECIMEN:	200 mm (8-inch) LONG, 50 mm (2-inch) WIDE, 1.6 mm (0.063-inch) THICK
TEST CONDITIONS:	R = 0.1; FREQUENCY 10 Hz MAXIMUM LOAD FOR DOUBLE-LAP JOINTS, 33,400 N (7,500 LBS)
FILLER METAL:	4043
FAILURE LOCATION:	BASE METAL FOR BRAZE AND WELDBRAZE SPECIMENS HOLE EDGE FOR BOLTED SPECIMENS NUGGET EDGE FOR SPOT WELDED SPECIMENS

TYPE JOINT	OVERLAP	NUMBER OF SPOT WELDS ACROSS SPECIMEN WIDTH (1)	SPECIMEN CODE	CYCLES TO FAILURE	FILLET SIZE
FOUR BOLTS 6 mm (0.25-inch)DIA	50 mm (2-inch)		A1-4 A1-5 A1-6	>960,190 (2) >221,700 (2) >313,440 (2)	
SPOT WELD	19 mm (0.75-inch)	3 (SINGLE ROW)	A3-4 A3-5 A3-6	12,240 14,690 10,150	
BRAZE	19 mm (0.75-inch)		A5-2-3	429,060	SMALL
WELDBRAZE	19 mm (0.75 inch)	1	B5-2-3	367,100	MEDIUM
		2	B6-2-3 B8-1-2 B9-2-3 B11-2-3 B6-4D B6-5D	153,430 190,000 242,550 157,310 165,840 313,060	MEDIUM MEDIUM LARGE MEDIUM SMALL LARGE
		3	B2-2-3	124,420	SMALL
BRAZE	38 mm (1.5-inch)		A4-2-3	>371,340 (2)	LARGE
WELDBRAZE	38 mm (1.5-inch)	6 (DOUBLE ROW)	B1-2-3	>177,780 (2)	LARGE
		3 (SINGLE ROW)	B3-2-3	>138,220 (2)	MEDIUM
	50 mm (2.0-inch)	4 (DOUBLE ROW)	A6-1D A6-3D	>589,140 (2) >1,349,480 (2)	MEDIUM MEDIUM

(1) SPOT WELD SPACING IS 13 mm (0.5-inch) FOR THREE SPOT WELDS, AND 25 mm (1.0-inch) FOR TWO SPOTWELDS
(2) FAILURE IN GRIP AREA OR GRIP RADIUS

AD-A054 042 NORTHROP CORP HAWTHORNE CA AIRCRAFT GROUP F/G 1/3
WELDBRAZE AIRFRAME COMPONENTS.(U)
NOV 77 R G HOCKER F33615-76-C-5111
UNCLASSIFIED NOR-77-115 AFML-TR-77-171 NL

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High Load Transfer Joints (Single-Lap Joints): The fatigue data for the high load transfer joint is presented in Table 19 for single-lap joints. The same maximum load was used for all but three of the specimens so that direct comparisons could be made between the four types of joints: bolted, spot welded, brazed and weldbrazed.

When comparing data for the single-lap specimens, it can be seen that the fatigue life of the brazed joint is equal to that of the weldbraze joint and that the fatigue life of the spot welded joint was much lower than the fatigue life of the weldbraze joint. However, the average fatigue life for the bolted joint (single lap) was greater than the average fatigue life of the weldbraze joint with the large overlap; i.e., 183,000 cycles vs 108,000 cycles.

The average life of a spot-welded joint was only 26,000 cycles vs 108,000 cycles for the weldbrazed joint for a 38mm (1.5 inch) overlap; and only 6,000 cycles vs 50,000 cycles for a 19mm (0.75 inch) overlap. Failure occurred at the edge of the nugget in the spot welded joints. However, failure occurred at the overlap edge in the base metal for weldbrazed and brazed joints. Therefore, the stress distributing behavior of the filler metal was responsible for a significant increase in the fatigue life of a weldbrazed joint over that of a spot-welded joint for single-lap joints. Since failure always occurred at the overlap edge in the base metal for the weldbraze joints, and since the fatigue life of the brazed joint was equal to that of the weldbrazed joint, the spot-weld spacing, i.e., one, two, or three spots, had no influence on the weldbraze joint strength for the single-lap, high-load transfer joint design.

The effect of overlap distance and fillet size for weldbrazed single-lap joints on fatigue life is presented in Figure 35. It can be seen that the fatigue life can be improved by increasing the overlap distance or by increasing the fillet size from very small to large. However, it has been determined that the filler-metal fillets will be small or very small for weldbraze joints that have been brazed in a vertical position. Therefore, fillet size is not a variable that can be controlled in all cases and should not be considered as a means of obtaining higher fatigue strength in aircraft components. Increasing the overlap would increase the weight of the joint.

It is difficult to compare the fatigue behavior of a bolted joint and a weldbrazed joint. The standard design for a bolted or riveted joint usually allows for at least two rows of fasteners which results in a large overlap, which increases the rigidity of the

TABLE 19. FATIGUE BEHAVIOR OF HIGH LOAD TRANSFER Ti-6Al-4V JOINTS — SINGLE-LAP JOINTS

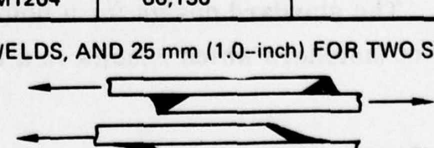
SPECIMEN: 200 mm (8-inch) LONG, 50 mm (2-inch) WIDE, 1.6 mm (0.063-inch) THICK

TEST CONDITIONS: R = 0.1; FREQUENCY, 10 Hz
MAXIMUM LOAD FOR SINGLE-LAP JOINTS, 16,700 N (3,750 LBS)

FAILURE LOCATION: BASE METAL FOR BRAZE AND WELDBRAZE SPECIMENS
HOLE EDGE FOR BOLTED SPECIMENS
NUGGET EDGE FOR SPOT WELDED SPECIMENS

TYPE JOINT	OVERLAP	NUMBER OF SPOT WELDS ACROSS SPECIMEN WIDTH (1)	SPECIMEN CODE	CYCLES TO FAILURE	FILLET SIZE
FOUR BOLTS 6 mm (0.25-inch) DIA	50 mm (2-inch)		A1-1	108,060	
			-2	178,490	
			-3	261,740	
SPOT WELD	38 mm (1.5-inch)	3 (DOUBLE ROW)	A2-1	26,550	
			-2	(99,540) (2)	
			-3	(304,940) (3)	
	19 mm (0.75-inch)	3 (SINGLE ROW)	A3-1	6,670	
			-2	4,740	
			-3	(31,920) (2)	
BRAZE WITH 4043 FILLER METAL	38 mm (1.5-inch)		A4-1	94,800	MEDIUM
	19 mm (0.75-inch)		A5-1	49,570	SMALL
WELDBRAZE WITH 4043 FILLER METAL	38 mm (1.5-inch)	3 (DOUBLE ROW)	B1-1	137,610	LARGE
		3 (SINGLE ROW)	B3-1	76,230	VERY SMALL
		1	B4-1	111,220	MEDIUM
	19 mm (0.75-inch)	3 (SINGLE ROW)	B2-1	44,100	VERY SMALL
		1	B5-1	51,480	SMALL
		2	B6-1	57,100	MEDIUM
		2	B7-1	47,500	VERY SMALL
		2	B8-3	70,800	LARGE
		2	B9-1	75,270	LARGE (4)
		2	B10-1	58,130	SMALL (5)
		2	B11-1	47,600	SMALL
WELDBRAZE WITH 3003 FILLER METAL	19 mm (0.75-inch)	2	B3003-1	69,670	MEDIUM
		2	B3003-2	72,500	LARGE
WELDBRAZE WITH 1100 FILLER METAL	19 mm (0.75-inch)	2	B1100-1	67,820	LARGE
		2	B1100-2	96,680 (7)	LARGE
MACHINED JOINT (6)	19 mm (0.75-inch)		M1203	129,590	
			M1204	86,130	

(1) SPOT WELD SPACING IS 13 mm (0.5-inch) FOR THREE SPOT WELDS, AND 25 mm (1.0-inch) FOR TWO SPOTWELDS
(2) MAXIMUM LOAD: 11,100N (2,500 LBS)
(3) MAXIMUM LOAD: 8,000N (1,800 LBS)
(4) INSIDE 30° BEVEL AT OVERLAP EDGE = LARGE FILLET
(5) OUTSIDE 30° BEVEL AT OVERLAP EDGE = SMALL FILLET



(6) SINGLE-LAP SPECIMEN MACHINED FROM 3.2 mm (0.125-inch) THICK SHEET TO OBTAIN LEG THICKNESS EQUAL TO THAT OF THE OTHER SPECIMENS. THE RADIUS AT THE OVERLAP EDGE WAS 0.13 mm (0.005-inch)
(7) INTERFACE FAILURE

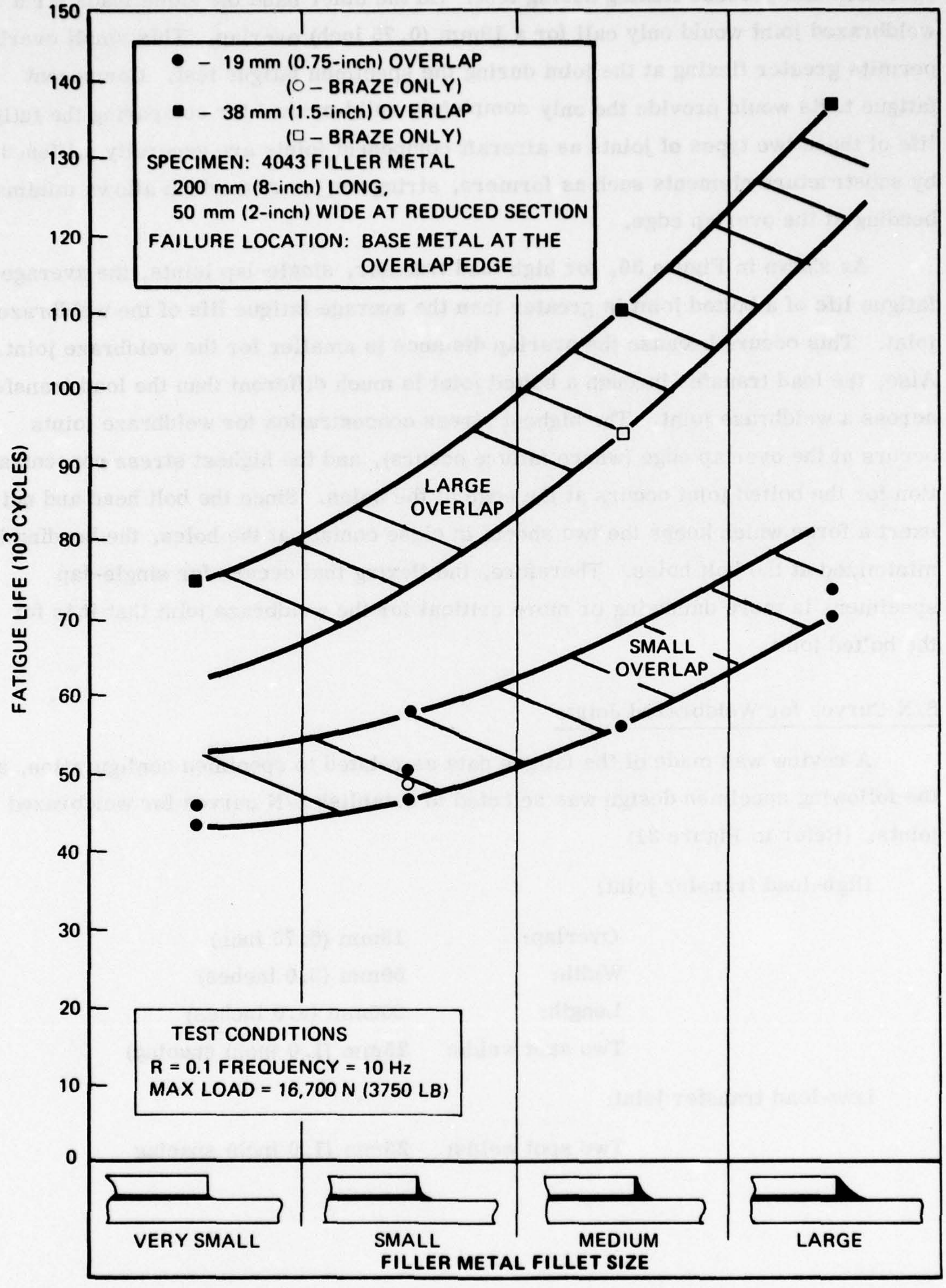


FIGURE 35. FATIGUE BEHAVIOR OF WELDBRAZE SINGLE-LAP Ti-6Al-4V JOINTS AS RELATED TO FILLET SIZE AND OVERLAP

specimen and reduces flexing during test. On the other hand the same loads for a weldbrazed joint would only call for a 19mm (0.75 inch) overlap. This small overlap permits greater flexing at the joint during the specimen fatigue test. Component fatigue tests would provide the only completely valid method for comparing the fatigue life of these two types of joints as aircraft component joints are generally stiffened by substructure elements such as formers, stringers, or ribs which allows minimal bending at the overlap edge.

As shown in Figure 36, for high load transfer, single-lap joints, the average fatigue life of a bolted joint is greater than the average fatigue life of the weldbraze joint. This occurs because the overlap distance is smaller for the weldbraze joint. Also, the load transfer through a bolted joint is much different than the load transfer across a weldbraze joint. The highest stress concentration for weldbraze joints occurs at the overlap edge (where failure occurs), and the highest stress concentration for the bolted joint occurs at the edge of the holes. Since the bolt head and nut exert a force which keeps the two sheets in close contact at the holes, the bending is minimized at the bolt holes. Therefore, the flexing that occurs for single-lap specimens is more damaging or more critical for the weldbraze joint that it is for the bolted joint.

S/N Curves for Weldbrazed Joints

A review was made of the fatigue data as related to specimen configuration, and the following specimen design was selected to establish S/N curves for weldbrazed joints: (Refer to Figure 31)

High-load transfer joint:

Overlap:	19mm (0.75 inch)
Width:	50mm (2.0 inches)
Length:	200mm (8.0 inches)
Two spot welds:	25mm (1.0 inch) spacing)

Low-load transfer joint:

Two spot welds:	25mm (1.0 inch) spacing

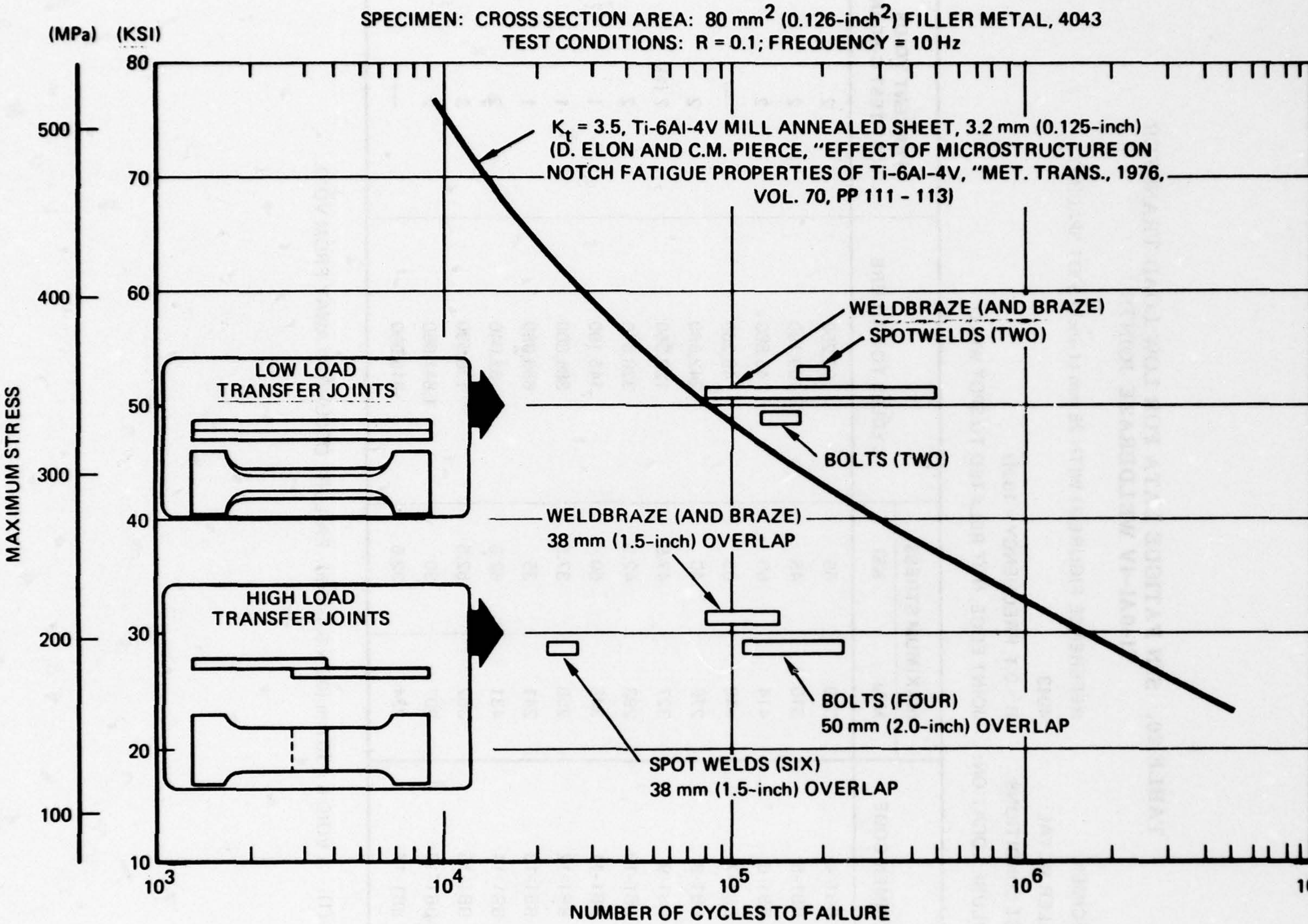


FIGURE 36. FATIGUE BEHAVIOR FOR Ti-6Al-4V JOINTS

TABLE 20. S/N FATIGUE DATA FOR LOW LOAD TRANSFER Ti-6Al-4V WELDBRAZE JOINTS

SPECIMEN: REFERENCE FIGURE 31 WITH 25 mm (1-inch) SPOT SPACING

FILLER METAL: 4043

TEST CONDITIONS: R = 0.1, FREQUENCY = 10 Hz

FAILURE LOCATION: JOINT EDGE, NOT RELATED TO SPOT WELD

SPECIMEN CODE	MAXIMUM STRESS		CYCLES TO FAILURE	PERCENT VOIDS (POST TEST C-SCAN)
	MPa	KSI		
BB1-4	379	55	90,250	2
BB1-5	310	45	169,190	2
BB1-6	414	60	45,860	2
BB1-7	448	65	49,260	—
BB1-8	276	40	242,590	2
BB1-9	327	47.5	120,650	7 (1)
BB1-10	293	42.5	328,970	2
BB1-11	345	50	146,190	1
BB1-12	258	37.5	385,800	1
BB1-13	241	35	656,080	1
BB1-14	431	62.5	62,040	2
BB1-15	362	52.5	136,590	3
BB1-16	207	30	1,841,060	2
BB1-17	224	32.5	815,590	—

(1) A VOID 5 x 10 mm (0.2 x 0.4-inch). FAILURE OCCURRED AWAY FROM VOID.

The S/N fatigue data generated with these specimens are presented in Table 20 and Table 21, and in Figure 37. The S/N curve for the low-load transfer joint is nearly coincident with that of notched Ti-6Al-4V, $K_t = 3.5$, shown in Figure 36.

Attempts were made to measure crack propagation rates in weldbrazed Ti-6Al-4V joints. As shown in Table 21, the number of cycles to failure occurred within 1% of the number of cycles to initiate a crack approximately 1.3mm (0.050 inch) long for most of the high-load transfer specimens. The exceptions were specimens B6-9, B6-11, and B6-12 for which the crack initiation occurred within 11%, 7%, and 4% of the cycles to failure, respectively. Since all failures occurred through this thickness of the base metal at the edge of the overlap, rapid crack propagation for this type of specimen is to be expected.

Specimen B6-9 which indicated the slowest crack propagation rate was one of the highest stressed specimens. It began to fail through the braze filler metal at the joint in addition to the failure through the base metal. In fact, a 45% delamination at the joint was measured by ultrasonic C-scan inspection after failure had occurred through the base metal. This indicates that a reduction in overlap could result in joint failure, with a probable reduction in fatigue life.

Formation of Ti-Al Intermetallic Compound Layer

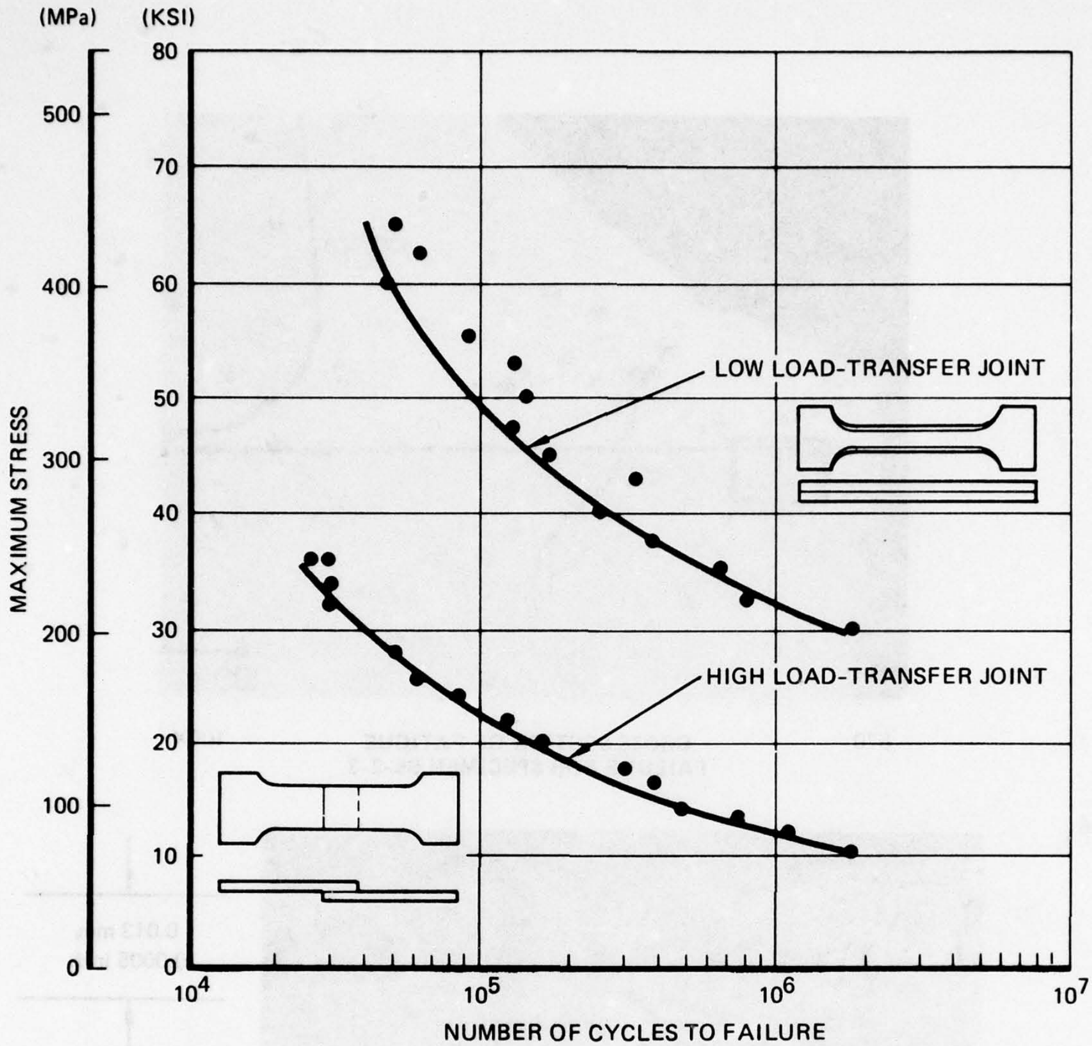
Some of the fatigue failures were analyzed with the scanning electron microscope (SEM). This analysis revealed that a Ti-Al intermetallic compound layer, approximately 0.012mm (0.0005 inch) thick, had been formed along the Ti-6Al-4V/4043 filler-metal interface. Further examination revealed that this layer contained many cracks and that fatigue failure for the high-load transfer single-lap specimen initiated at these cracks and then progressed through the base metal at the joint edge. An example of secondary fatigue cracks originating in this brittle layer is shown in Figure 38. Additional SEM analyses were made for other filler metal weldbraze systems. The results of these analyses showed that an intermetallic compound was formed even at brazing temperatures as low as 890K (1140F). The intermetallic compound layer thicknesses for several filler metals and braze temperatures are as follows:

TABLE 21. S/N FATIGUE DATA FOR HIGH LOAD TRANSFER Ti-6Al-4V WELDBRAZE JOINTS

SPECIMEN: 200 mm (8-inch) LONG, 50 mm (2-inch) WIDE, 1.6 mm (0.063-inch) THICK, 19 mm (0.75-inch) OVERLAP, TWO SPOT WELDS: 25 mm (1-inch) SPACING
FILLER METAL: 4043
TEST CONDITIONS: R = 0.1; FREQUENCY = 10 Hz
FAILURE LOCATION: BASE METAL AT OVERLAP EDGE

SPECIMEN CODE	MAXIMUM STRESS MPa	KSI	CYCLES TO CRACK INITIATION (1)	CYCLES TO FAILURE	PERCENT VOIDS (POST TEST C-SCAN) (2)
B6-4	166	24	—	86,570	2
B6-5	221	32	29,710	29,760	3
B6-6	138	20	159,210	160,610	1
B6-7	193	28	52,040	52,600	5
B6-8	124	18	297,810	298,770	2
B6-9	248	36	26,230	29,500	45 (3)
B6-10	110	16	377,800	379,540	2
B6-11	176	25.6	57,010	61,610	2
B6-12	152	22	117,710	123,180	2
B6-13	97	14	486,720	488,280	2
B6-14	83	12	1,049,520	1,052,520	11 (4)
B6-15	69	10	1,765,250	1,768,520	2
B6-16	90	13	737,380	741,500	2
B6-17	234	34	—	30,040	5 (5)
B6-18	248	36	—	24,940	2

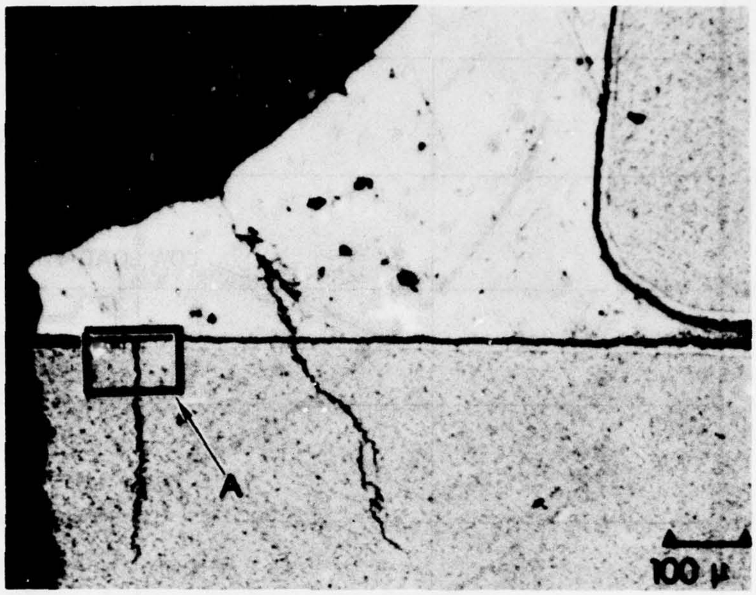
(1) INITIAL DETECTED CRACK LENGTH WAS APPROXIMATELY 1.3 mm (0.050-inch).
(2) THE MAXIMUM DIAMETER FOR THE VOIDS WAS 1.9 mm (0.075-inch).
(3) PARTIAL DELAMINATION OCCURRED DURING THE FATIGUE TEST.
(4) THREE VOIDS WITH APPROXIMATE 5 mm (0.2-inch) DIAMETERS.
(5) ONE VOID WITH A 6 mm (0.25-inch) DIAMETER.



HIGH LOAD-TRANSFER SPECIMEN:	OVERLAP:	19 mm (0.75-inch)
	WIDTH:	50 mm (2.0-inch)
LOW LOAD-TRANSFER SPECIMEN:	BASE WIDTH:	32 mm (1.25-inch)
	TOP WIDTH:	19 mm (0.75-inch)

SHEET THICKNESS:	1.6 mm (0.063-inch)
FILLER METAL:	4043
TEST CONDITIONS:	R = 0.1, FREQUENCY = 10 Hz

FIGURE 37. S-N FATIGUE CURVES FOR WELDBRAZED Ti-6Al-4V



870 CROSS SECTION OF FATIGUE FAILURE FOR SPECIMEN B5-2-3 100X

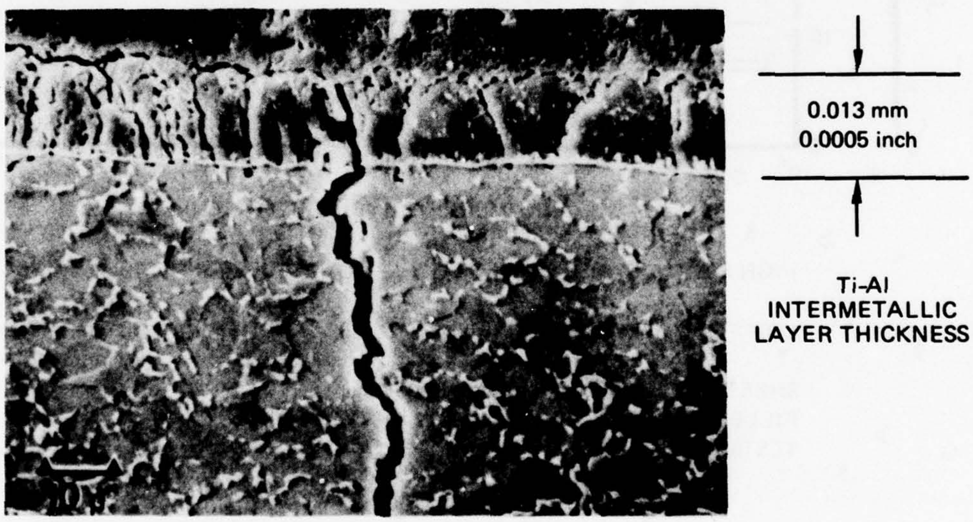


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FIGURE 38. SECONDARY FATIGUE CRACKS EXTENDING FROM THE BRITTLE Ti-Al INTERMETALLIC LAYER

Filler Metal	Braze Temperature	Ti-Al Intermetallic Layer Thickness
4043	920K (1200F)	0.013mm (0.0005 inch)
2319	935K (1220F)	0.005mm (0.0002 inch)
AVCO 48	890K (1140F)	0.002mm (0.0001 inch)
5052	935K (1220F)	0.002mm (0.0001 inch)
3003	945K (1240F)	0.002mm (0.0001 inch)
201	940K (1230F)	0.002mm (0.0001 inch)
1100	935K (1220F)	0.001mm (0.00006 inch)

Additional measurements were made on other test specimens and these results indicate that intermetallic layer thickness varied in the range of 0.002mm to 0.013mm (0.0001 inch to 0.0005 inch) for most of these filler metals. The time at the brazing temperature ranged from 15 to 30 minutes for these test specimens.

Since filler metals 3003 and 1100 seemed to have the thinnest layer, fatigue tests were conducted for high-load transfer single-lap weldbraze joints fabricated with these filler metals. The results are presented in Table 19. The two specimens for the 3003 weldbraze system had fatigue lives of 69,670 cycles and 72,500 cycles and the two specimens for the 1100 weldbraze system had fatigue lives of 67,820 and 96,680. The fillet size was medium to large for both of these weldbraze systems. These results were very similar to the fatigue life for the 4043 system for medium to large fillets; i.e., 57,100, 70,800, and 75,270 cycles. It should be pointed out that specimen B1100-2 (96,680 cycles) failed at the interface rather than through the base metal. Therefore, the thickness of the intermetallic layer (within the range noted above) appears not to be a critical factor for improved fatigue behavior.

An investigation was made under Northrop IRAD effort to determine the geometric effect of a high-load transfer joint design on the fatigue behavior of titanium. Two fatigue specimens were machined from 3.2mm (0.125 inch) thick sheet to simulate a single-lap joint design having an overlap of 19mm (0.75 inch) and an overlap fillet radius of approximately 0.12mm (0.005 inch). These machined specimens were heated to 920K (1200F) for 30 minutes in order to stress relieve the titanium and to simulate the thermal cycle of a typical weldbrazed joint. The fatigue life for these two specimens was 86,130 cycles and 129,590 cycles, Table 19.

The fatigue life of weldbrazed specimens with a small fillet radius was 51,480, 58,130, and 47,600 cycles. Although the fatigue life of the machined joint is greater

than for the weldbraze joints, it is believed that the geometric effect of the single-lap joint design, i.e., stress concentration factor, is the major controlling factor for the fatigue life in the weldbrazed single-lap joint rather than the thin intermetallic compound layer formed during the braze cycle.

To show the effect of an increased radius, two additional fatigue specimens were machined identical to specimens M1203 and M1204, except that the fillet radius at the overlap edge was machined to 1.6mm (0.063 inch). The fatigue life of these specimens was greater than 1.1 million cycles and greater than 2.2 million cycles. Both tests were discontinued. These results show a fatigue life more than 10 times greater than that for the small radius specimens. Since aluminum is much softer and weaker than titanium, it is believed that its effect in reducing stress concentration at the overlap edge is much less and, therefore, the stress concentration for a weldbrazed specimen could be represented by a machined fillet radius approaching zero.

The two fillet radii evaluated for the machined titanium specimens corresponds to fillet sizes "very small" and "medium" for the weldbrazed specimens as shown in Figure 35. The average increase in fatigue life indicated in Figure 35 for these two radii was only 12,000 cycles, i.e., 48,000 cycles to 60,000 cycles. However, the average increase in fatigue life for the corresponding fillet sizes in the machined titanium specimens was greater than 1,000,000 cycles, i.e., 108,000 cycles to greater than 1,600,000 cycles. Therefore, the effectiveness of aluminum filler metal for reducing stress concentration at the overlap edge is much less than that obtained by an equal fillet radius in a machined titanium specimen. A better representation of a weldbrazed joint by using a machined titanium specimen would be to machine an overlap fillet radius of only 0.02mm (0.001 inch) instead of the 0.13mm (0.005 inch) used for this investigation. The fatigue life of this proposed specimen would no doubt approach the fatigue life of the weldbraze joint much closer than did the two machined specimens with the 0.12mm (0.005 inch) radius. This, again, would emphasize that the overlap joint design (stress concentration factor) is the controlling factor for fatigue life rather than the thin brittle intermetallic layer on the titanium.

Weldbraze Property Summary

Based on the weldbraze properties presented in this report, braze temperature, and availability of the filler metal in wire form; summary ratings are presented for eight filler metals in Table 22. The lower the rating number. the higher the property rating, as shown in the Table. For example, filler metals 3003, 4043, 5052, and 1100

TABLE 22. FILLER-METAL/WELDBRAZE PROPERTY RATINGS

PROPERTY / FILLER-METAL	3003	4043	718	201	NO. 7	5052	1100	AVCO 48
LAP-SHEAR (1)	1	2	2	1	3	1	1	2
CROSS-TENSION (1)	1	1	1	3	3	2	1	2
STRESS-RUPTURE (1)	2	3	2	1	2	3	1	2
CORROSION RESISTANCE (2)	1	1	3	5	5	1	1	5
BRAZE TEMPERATURE (3)	3	1	1	3	1	2	2	1
AVAILABILITY (4)	1	1	1	1	5	1	1	5
TOTAL RATING (5)	9	9	10	14	19	10	7	17

RATING BASIS:

(1) LAP-SHEAR, CROSS-TENSION, AND STRESS RUPTURE RATINGS: 1 – BEST, 2 – GOOD, 3 – POOR

(2) CORROSION RESISTANCE RATINGS: 1 – EXCELLENT, 3 – AVERAGE, 5 – VERY POOR

(3) BRAZE TEMPERATURE RATINGS: 1 – 920K (1200F) OR LOWER, 2 – RANGE OF 920K (1200F) TO 927K (1220F), 3 – GREATER THAN 927K (1220F)

(4) AVAILABILITY: 1 – AVAILABLE IN WIRE FORM, 5 – NOT AVAILABLE IN WIRE FORM

(5) TOTAL RATING: THE LOWER RATING NUMBERS INDICATE BETTER OVERALL PROPERTIES

have a very good corrosion resistance and, therefore, were assigned a rating factor of 1 compared to filler metals 201 and No. 7 which have very poor corrosion resistance and were assigned a rating factor of 5. The ratings for corrosion resistance, braze temperature, and availability were weighted more heavily than the others due to their impact on service life and cost.

On the basis of this table filler metals 1100, 4043 and 3003 have the best overall properties. The overal rating for filler metals 718 and 5052 is nearly equal to the rating for filler metals 4043 and 3003. Filler metals 201, No. 7 and AVCO 48 have the lowest ratings.

WELDBRAZED AIRCRAFT STRUCTURE

A Ti-6Al-4V titanium former assembly, 53 cm (21-inch) high and 127 cm (50-inch) wide, was selected to demonstrate feasibility for fabricating an aircraft component using the weldbraze joining parameters developed during this program. This former assembly, Part Number 14-12308, is located in tne aft fuselage section of the Northrop F-5E fighter, as shown in Figure 39. The fabrication of this structure by weldbraze techniques demonstrates weldbraze capabilities for lap joints containing two, three, and four-layer combinations of varying titanium sheet thicknesses and demonstrates the replacement of more than 250 rivets, as shown in Figure 40.

The former components were saw-cut as required to provide parts for two former half sections. These half sections were then cleaned, spot welded, and brazed in a production vacuum furnace. Two edge members of the former seen in Figure 40 were aluminum and, therefore, could not be brazed with the titanium structure. The two former half sections allowed the use of two braze runs to help demonstrate repeatability of a production furnace to obtain successful weldbrazed structures.

The cleaning methods used for preparing the titanium and the 4043 filler metal were the same as those discussed earlier. The spot weld schedules were interpolated from Table 5 for similar thickness combinations. The sheet thicknesses contained in the former assembly included: 0.8mm (0.032 inch), 1.0mm (0.040 inch), 1.3mm (0.050 inch) and 1.6mm (0.63 inch). All of the joints in the former included at least two layers of the thicker sheet materials. Therefore, a weld schedule similar to that used for thickness combination No. 5 of Table 5 was used to make all the welds in the former assembly, i.e., 12 heat cycles, 6230 N (1400 lb.) electrode force, and a welding current range of 8000 to 10,000 amperes. This slightly lower welding current

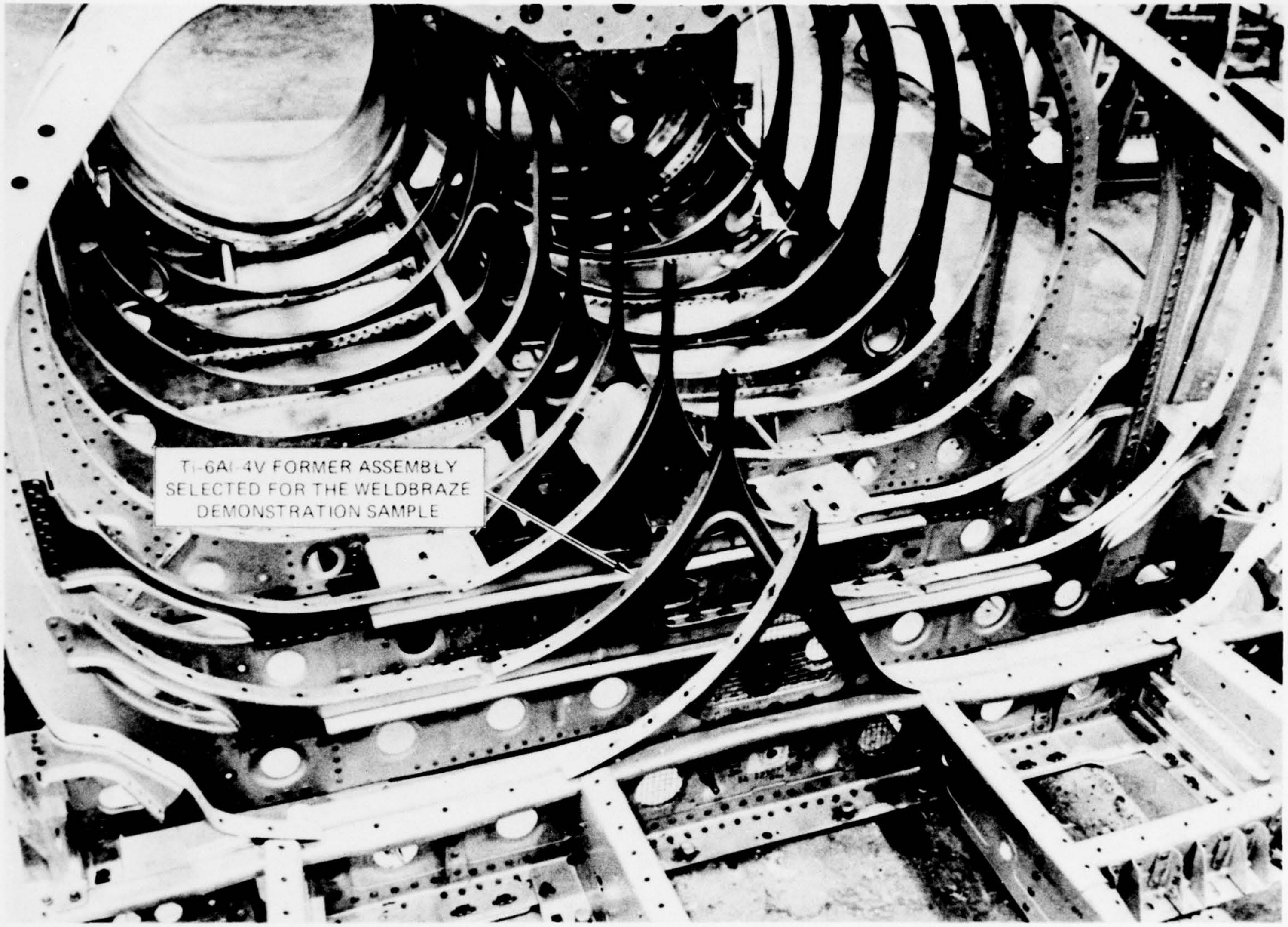

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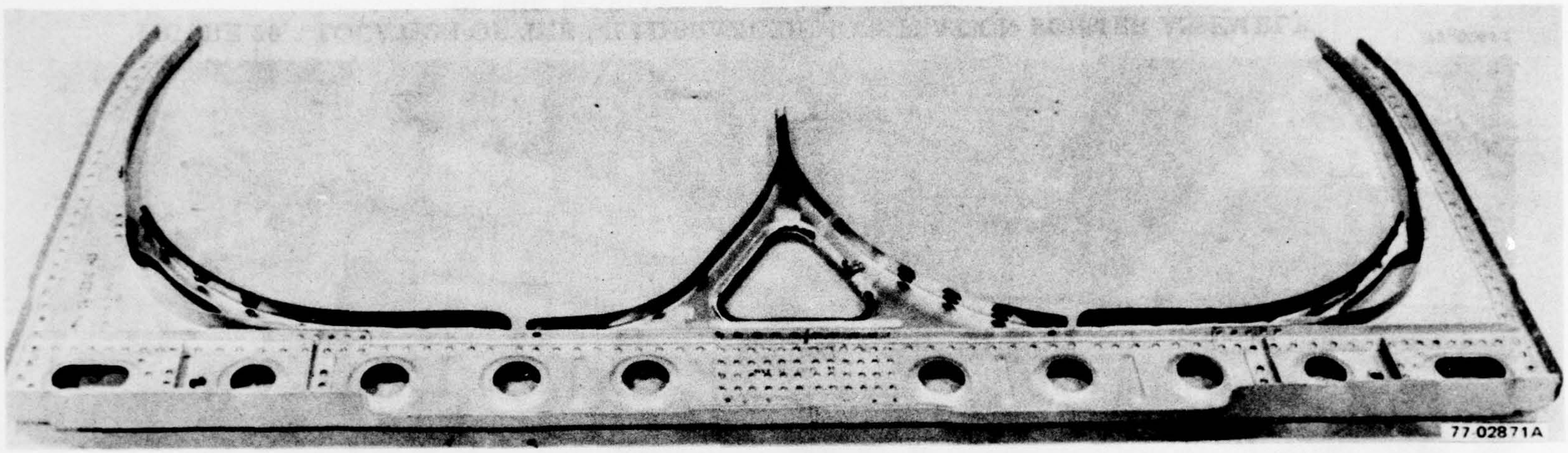
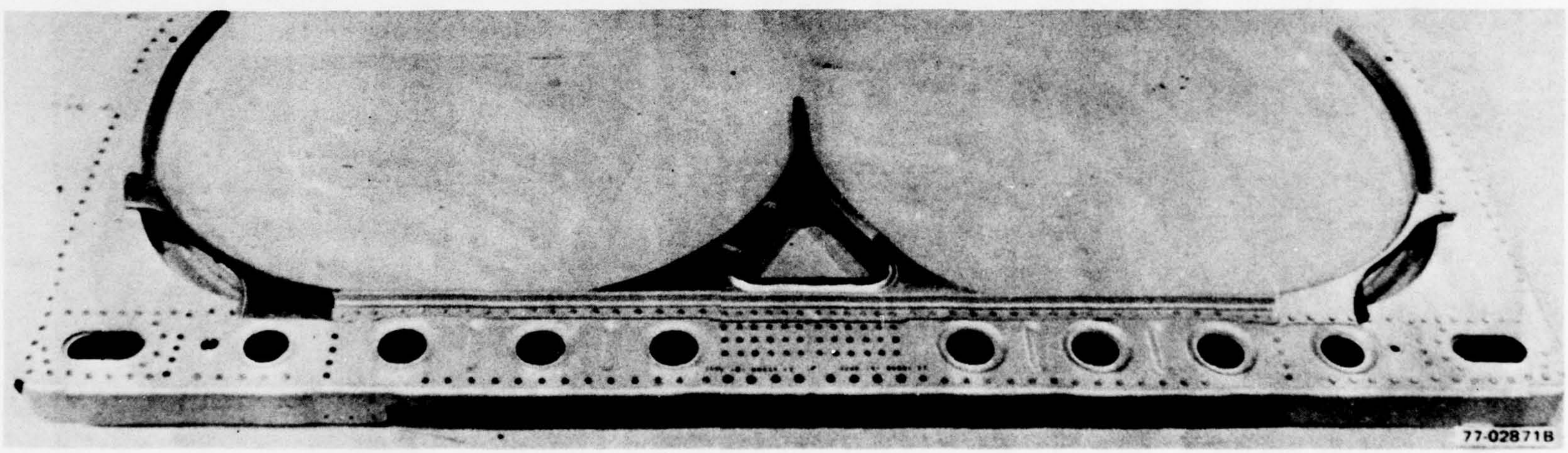
FIGURE 39. LOCATION OF THE WELDBRAZE DEMONSTRATION FORMER ASSEMBLY IN THE F-5E AFT FUSELAGE SECTION



BACK SURFACE



FRONT SURFACE

FIGURE 40. RIVETED Ti-6Al-4V FORMER ASSEMBLY, PART NO. 14-12308

was used because of the thinner sheet thicknesses used for the former joints. The large value for the electrode force was used to ensure good contact (prevent expulsion) in the multiple layer joints for which the fit up was not as good as is obtained for laboratory specimens. For poor access areas in which an offset electrode was used the electrode force was reduced to 3115 N (700 lb.) to prevent the electrode from buckling. All nugget diameters were greater than 5mm (0.2 inch) indicating that Class A welds had been obtained, as shown in Table 6.

Filler metal was placed at the edges of the joints and held in place by spot welding aluminum foil tabs over the filler metal. Titanium foil tabs were used for the inverted position joint to prevent the filler metal from dropping off during the braze cycle. The quantity of filler metal required was calculated from the formula established early in the program, i.e., 0.05 grams per 0.025mm (0.001 inch) joint gap per 645 mm^2 (square inch) of lap area. This formula provided a good estimate for areas of uniform joint gap dimensions, however, 50% additional filler metal was used to allow for joggle gaps and for large bend radii. A total of 60 grams was used to braze the entire former, or 30 grams for each half section.

The former half sections were then brazed in an ABAR cold wall vacuum furnace having working zone dimensions of 460mm (18 inch) high, 610mm (24 inch) wide, and 915mm (36-inches) deep. The thermal gradient within the working zone was within ±8K (15F).

A chromel-alumel thermocouple was spot welded to the center of the bottom edge and one thermocouple was placed at each end of the bottom edge to ensure adequate temperature control during the brazing cycle.

The former half section was placed in a titanium foil box approximately 75mm (3 inch) high, 530mm (21 inch) wide, and 690mm (27 inch) long. Six lap-shear specimens were positioned beside the part as a quality control check for each braze run. The following three-hour braze cycle was used:

590K (600F)	—	backfill with argon
810K (1000F)	—	5 min. hold
870K (1100F)	—	5 min. hold
900K (1160F)	—	4 min. hold
920K (1200F)	—	10 min. hold

Furnace cool to 590K (600F)

Argon cool to room temperature

The two braze runs were completely successful in obtaining excellent weldbrazed former half sections as seen in Figures 41, 42, and 43. The quality control lap-shear specimens tested after the braze runs showed full lap-shear strength, greater than 83MPa (12 ksi).

Non-Destructive Inspection

A visual examination of the weldbrazed former section showed 100% filler metal flow in the weldbrazed joints, Figure 43. Excellent wetting and fillet formation occurred for the former and for the quality control lap-shear specimens. Dimensional measurements were made prior to and after the braze cycle. The prior measurements revealed that there was a slight concave bow along the front surface bottom edge of the former half section, i.e., 3.2mm (0.12 inch). After the braze cycle the bow was reduced by one half. This was expected since filler metal, placed on the back surface, will tend to pull the part as the filler metal cools and shrinks. No other dimension changes occurred during the braze run. These results indicate that similar components would require no tooling to hold reasonable tolerances for a titanium component weldbrazed with the above parameters.

The former half sections were also radiographically inspected. Only a few minor voids were detected at the 90° bend along the lower edge of the former. These voids were present in only three locations and were less than 15% of the braze area per inch length along the bottom edge. In the left former section there were small voids at the joggles, i.e., at the center stiffener and at the lower edge. The right former section showed complete filler metal filling of these joggle locations. The minor voids detected by radiography were well defined and would not reduce the joint properties and would not be cause for rejection.

The successful fabrication of this former assembly by using the weldbrazing techniques developed for this program shows the feasibility of using the weldbrazing joining method to fabricate airframe components.

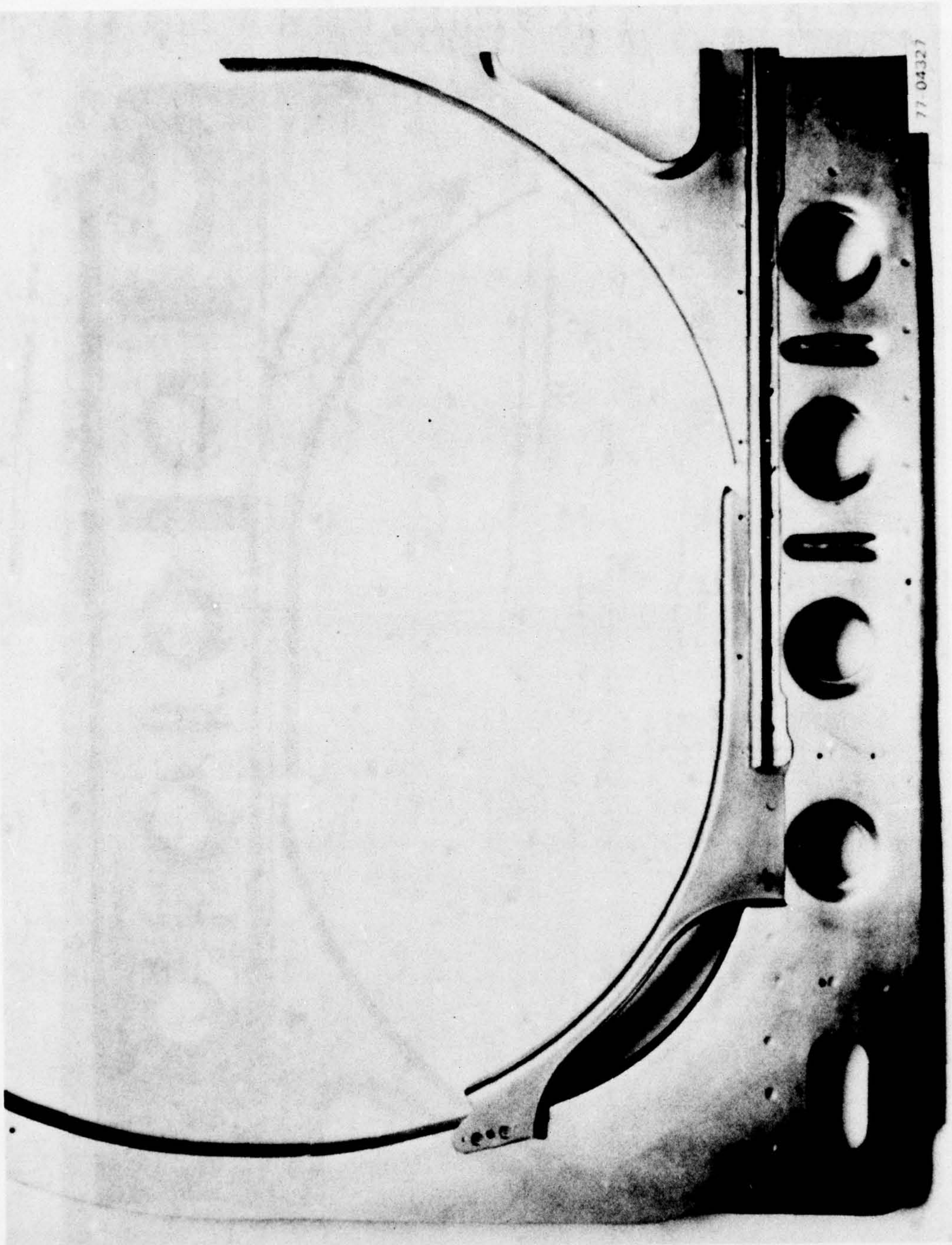


FIGURE 41. WELDBRAZED Ti-6Al-4V FORMER HALF SECTION – FRONT SURFACE

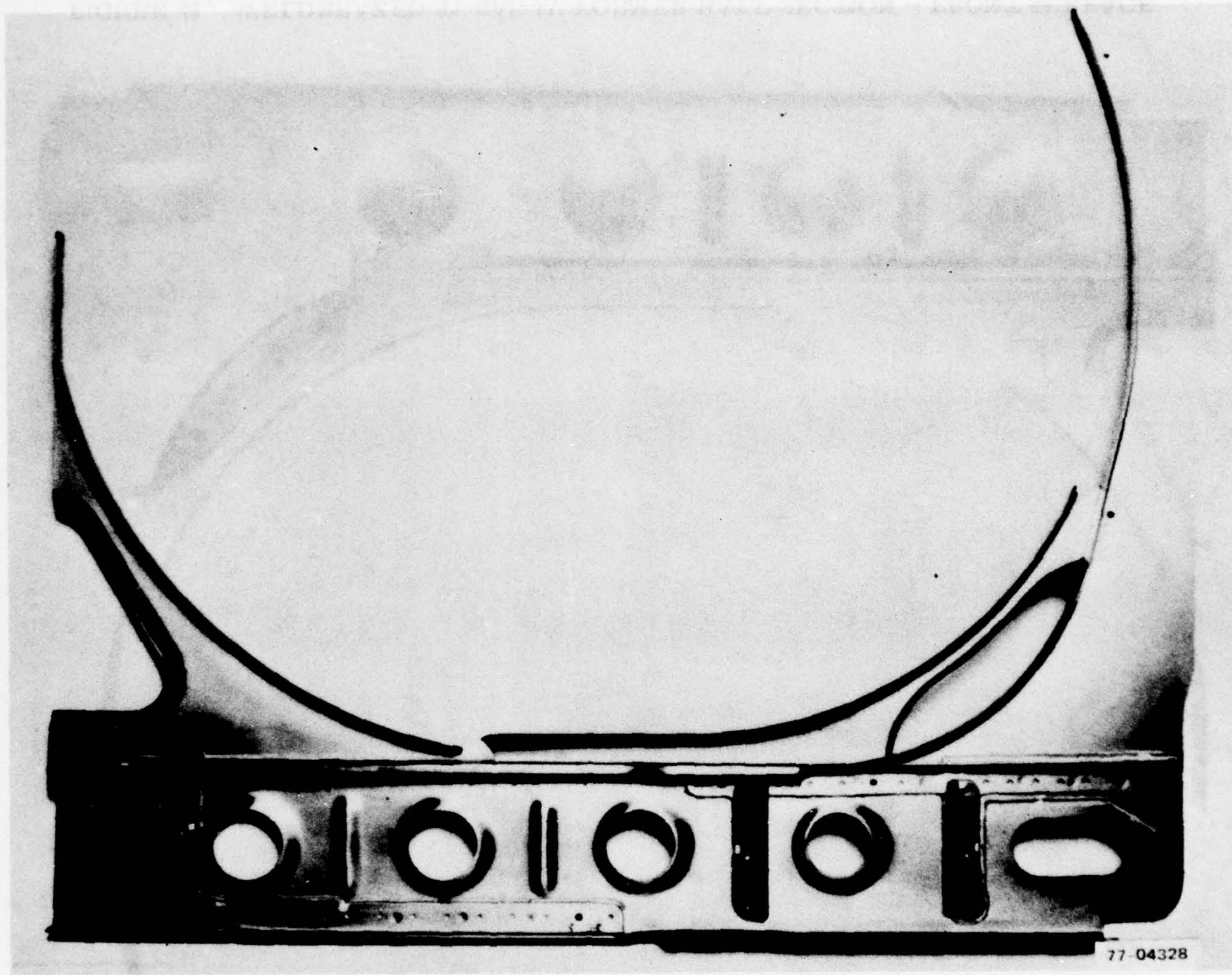
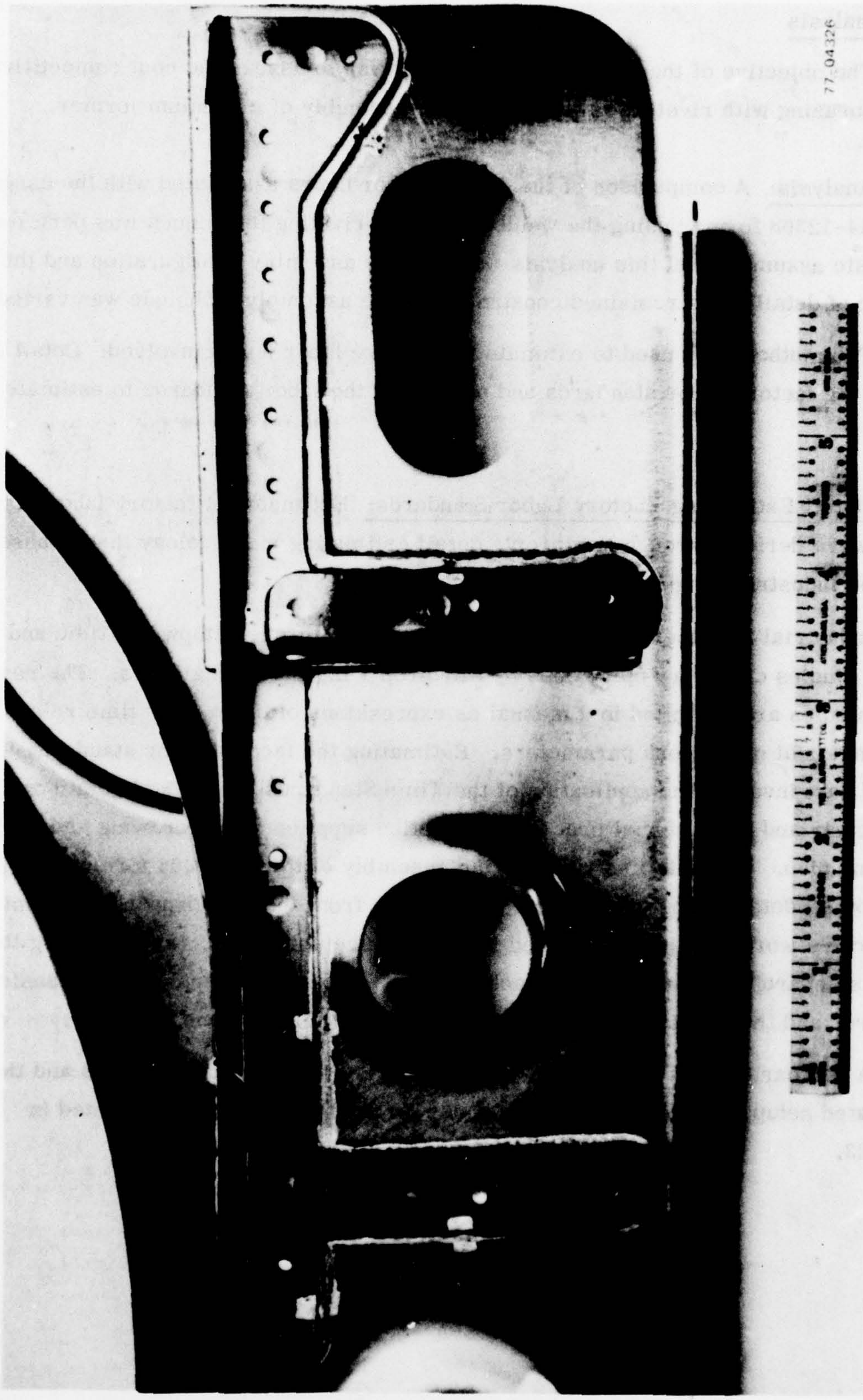


FIGURE 42. WELDBRAZED Ti-6Al-4V FORMER HALF SECTION – BACK SURFACE



BACK SURFACE

FIGURE 43. CORNER DETAIL OF THE WELDBRAZED FORMER

Cost Analysis

The objective of the cost analysis activity was to assess the cost competitiveness of weldbrazing with riveting as techniques for assembly of a titanium former.

Analysis: A comparison of the factory labor hours associated with the assembly of the 14-12308 former using the weldbrazing and riveting techniques was performed. The basic assumption of this analysis was that the assembly configuration and the number of detail parts remained constant; only the assembly technique was varied.

The methodology used to estimate the factory labor hours involved: Detail estimating the factory labor standards and projecting the labor standards to estimate total hours.

Detail Estimating Factory Labor Standards: Estimates of factory labor standard hours were derived through Northrop's detail estimating methodology that is based upon the Industrial Engineering Standards approach.

Industrial Engineering Standards are developed through stopwatch time and motion studies of factory operations by Northrop's industrial engineers. The results of the studies are compiled in a manual as expressions of basic work time related to part, material or process parameters. Estimating the factory labor standards for a defined part involves the application of the Time Standards Basic Data relationships to the part, and the material process description supplied by the drawing and manufacturing plan. The detail estimate of the assembly of the 14-12308 former was prepared by (1) determining the physical parameters from the part drawing, (2) identifying the discrete work elements described in the manufacturing plan, (3) identifying the "basic standard" corresponding to each work element, and (4) applying the "basic standard" and the appropriate parameter to obtain the labor standard hours.

A comparison of the assembly related operations for both techniques and the associated setup and runtime standard hours for each operation is presented in Table 23.

TABLE 23. COMPARISON OF FACTORY LABOR STANDARD HOURS FOR ASSEMBLY OF 14-12308 FORMER

RIVETING			WELDBRAZING			Δ%
	Setup	Run		Setup	Run	
Drill #40 Pilot Holes (Qty = 326)	0.40	0.450	Drill #40 Pilot Holes (Qty = 66)	0.40	0.091	<79.8%>
Assemble Parts	0.08	1.103	Assemble Parts	0.08	1.103	-0-
Attachment			Attachment			
Drill Holes from Pilots (Qty = 326)	0.999		Drill Holes from Pilots (Qty = 52)	0.159		
Install Fasteners (Qty = 326)	1.500		Install Fasteners (Qty = 52)	0.329		
			Spot Weld	0.317		
			Clean and Place Filler Metal	0.155		
			Prepare for Braze Cycle	0.250		
			Furnace Braze Monitoring *	0.202		
Subtotal Attachment Operations		2.499	Subtotal Attachment Operations		1.322	<47.1%>
Remove from Assembly Jig and Drill Holes for Nutplates (Qty = 52)	0.03	0.457	Remove from Furnace and Drill Holes for Nutplates (Qty = 52)	0.03	0.457	-0-
Identify and Rubber Stamp	0.01	0.005	Identify and Rubber Stamp	0.01	0.005	-0-
TOTAL	0.52	4.514	TOTAL	0.52	2.978	<30.5%>

*Furnace cycle time is not included.

The 30.5% labor hours savings achievable through weldbrazing can be attributed to the reduction in fasteners from 326 to 52. This reduction in fasteners means a decrease in the number of pilot holes and fastener holes to be drilled and a decrease in the number of fasteners to be installed. So although there are more operations in weldbrazing, the reduction in effort related to the fasteners results in a net labor savings.

Projection of Labor Standard Hours: The standards represent only the basic work content of a task and do not account for other elements which are experienced in a real production environment such as fatigue, breaks, delays, etc. Figure 44 illustrates the content of factory labor and the relationship of the basic work content, or "pure" labor as quantified by the standards, to the total.

To account for the other elements of factory labor which are experienced in a real production environment, the factory labor standards were adjusted by the application of a variance factor and an improvement curve slope. Figure 45 illustrates factory labor hours projection procedure and depicts the relationship of factory labor standards, variance factor and improvement curves. In projecting factory labor costs from standards, Northrop applied a variance factor of 1.85 at T_{1000} to the total factory labor standards. This point represented the factory hours required to manufacture the 1000th unit. From this point, a line was projected to unit one (T_1) following an 82% improvement curve slope. The 1.85 variance factor and 82% improvement curve slope were developed from Northrop's production experience related to assembly operations.

The table below summarizes the results of the factory labor hours projection for the former assembly.

	Riveting	Weldbrazing	Δ%
Standard Hours			
Setup	0.52	0.52	
Run	4.514	2.978	
Total	5.034	3.498	<30.5%>
T_1 Hours	67.32	46.78	<30.5%>
T_{1000} Hours	9.31	6.47	<30.5%>

Assembly of the 14-12308 former utilizing the weldbrazing technique results in a 30.5% savings in factory labor hours as compared with the riveting technique.

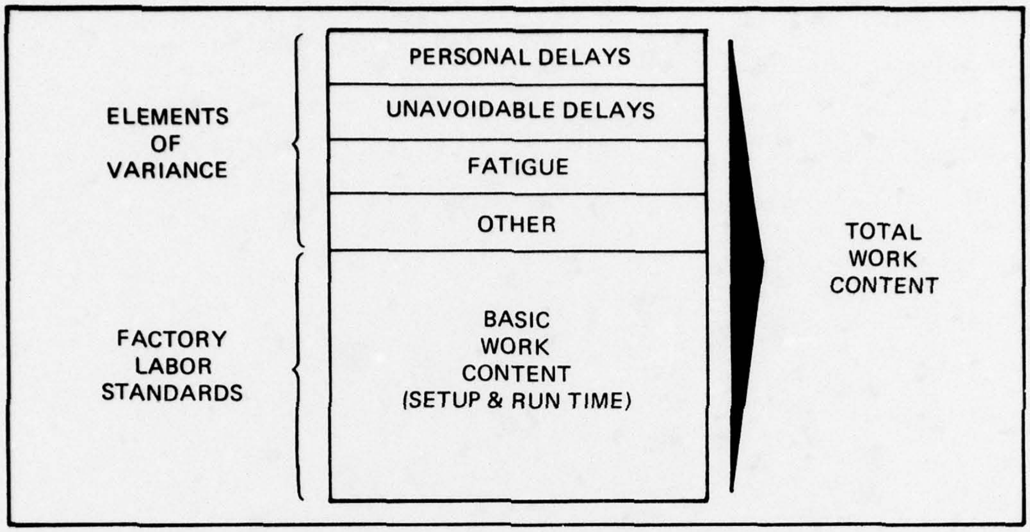


FIGURE 44. CONTENT OF FACTORY LABOR

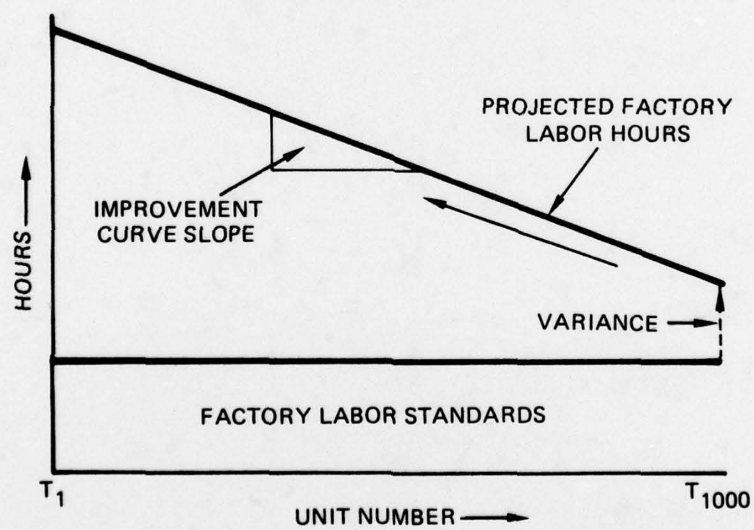


FIGURE 45. FACTORY LABOR STANDARD HOURS PROJECTION

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Filler metals 4043 and 1100 provide the best combination of weldbraze joint properties in terms of joint appearance, corrosion resistance, lap-shear strength, stress-rupture strength, and comparatively low brazing temperature.

2. Standard manufacturing cleaning procedures as defined in this report are suitable for titanium weldbraze joint preparation.

3. High quality spot welds are easily obtained for titanium lap joints. The wide range of spot weld schedule parameters permits spot welds to be made with a high degree of process latitude. Nugget cracking is not a problem for spot welds made with the recommended welding schedules.

4. Ultrasonic techniques and radiography can be used effectively for detecting voids in weldbrazed joints.

5. Typical airframe former assemblies can be weldbrazed with minimum warpage or distortion.

6. Weldbrazing can significantly reduce assembly cost as compared to riveting.

7. The room temperature lap-shear strength of standard weldbraze joints (overlap per MIL-W-6858C) is equal to base material strength, i.e., fails in the base metal not in the joint.

8. The high-load transfer fatigue life of weldbrazed joints is a factor of 10 greater than that for spot welded joints.

9. Fatigue strength of weldbrazed joints and bolted joints is approximately the same, for the low-load transfer joint.

RECOMMENDATIONS

The results of this program and of other similar programs show that the weld-brazing joining method can become a standard manufacturing procedure. Before this can occur, several areas should be further investigated including cost effectivity of weldbraze joining, optimized joint design for lower manufacturing cost and reduced weight, design data requirements, and quality control criteria. It is recommended that the following work be conducted to further establish the weldbraze joining technique for aircraft structures:

1. Design, fabricate, and test actual aircraft structures or subscale components using simulated service conditions. Compare riveted and weldbrazed components.
2. Conduct a weldbraze application survey to determine what portions of an aircraft might benefit by the weldbraze joining method in terms of modified joint design, lower-fabrication costs, and reduced weight.
3. Conduct a design data requirement study to determine what additional weldbraze property data is required.
4. Conduct additional manufacturing cost evaluations to compare the riveted joining method with the weldbraze joining method.
5. Develop retort brazing methods in large heat treat furnaces and compare to the more costly, limited size, vacuum furnaces.
6. Determine the effects of void size and location in weldbrazed joints on the fatigue strength of high-load transfer joints to establish quality control criteria.
7. Determine the effects of salt fog exposure on subsequent fatigue properties of weldbrazed joints.
8. Conduct additional stress-rupture tests (for several filler metals and for time periods less than 50 hours) to determine the threshold stress-time condition for which cracking initiates in the filler metal. Interface filler-metal cracks could propagate under fatigue loading.
9. Conduct elevated temperature fatigue tests.
10. Develop more cost effective filler-metal placement methods.

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